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OUTLINES OF MINERALOGY

GRENVILLE A. J. COLE

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OUTLINES OF MINERALOGY

FOR GEOLOGICAL STUDENTS

BY

GRENVILLE A. J. COLE

Professor of Geology in the Royal College of Science for Ireland

WITH DIAGRAMS

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PREFACE

THE subject of Mineralogy is of fundamental interest to workers in many sciences. A century ago, the study of the materials that diversify the earth's crust was regarded as a natural occupation among men of taste and leisure. The "grand tour" of Europe, which became more and more possible at the close of the Napoleonic wars, opened the eyes of many to the wealth of mineral substances that had been utilised for the decoration of buildings in all lands influenced by Rome. A knowledge of what the miners of Saxon race had done in the mountains of Bohemia and of Hungary attracted attention to the immense variety of metallic ores. The brilliant results of Romé de l'Isle and Haüy in the measurement of crystal-angles drew the mathematicians also towards mineral observation. The chemist found in specimens from remote localities elements new to science, suggesting by their properties an ordered scheme of classification. Mineralogy, in fact, is the natural history branch of chemistry; it is obviously of the first importance to the miner and the metallurgist; and the geologist, whether as a student of earth-structure or as a prospector in the field, finds that the solution of his broad problems depends ultimately upon the characters of minerals. The agricultural enquirer, moreover, soon becomes concerned with the mineralogy of soils. Though few persons can select mineralogy as the object of a specialised career, the outlines of the science clearly make a wide appeal. An attempt has been made in the present book to treat minerals as constituents of the earth, and as influencing its features and its surface. The book is thus primarily intended for those who are interested in geology, and who find themselves in need of an introduction to the classificatory details of the larger works of reference. Especial stress is laid on the modes of occurrence of minerals in rocks, and hence often on their massive representatives rather than on well crystallised types. To the geologist, a realisation of a mineral in its habit in the field is of more importance than its place in the cabinet of the curious. On the other hand, he should be fully aware of the methods by which species are determined, and of the characters assumed by minerals as they grow. Preliminary conceptions may be gained from the following chapters, and from the experimental tests suggested in them, which may lead him to a closer acquaintance with the science of mineralogy. At the same time, he may perceive how much of our knowledge of physical geology at the present day is due to the pioneers, who viewed rocks as aggregates of minerals and as the natural home of the crystals which they sought.

I have added references here and there to literature and original observations, mostly of modern date, which will, I trust, encourage further reading in what is a very living science.

The Publishers have kindly allowed me the use of a number of illustrations from H. Bauerman's "Systematic Mineralogy," and these have been supplemented by diagrams drawn by Mr. M. W. Gavin and Mr. J. J. Burke, and by sketches of minerals made by the latter artist, mostly from material that I have found serviceable in teaching work.

GRENVILLE A. J. COLE.

DUBLIN,
August, 1913.

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OUTLINES OF MINERALOGY FOR GEOLOGICAL STUDENTS

PART I

THE CHARACTERS OF MINERALS

CHAPTER I

THE NATURE OF A MINERAL

No definition will satisfy all those who deal with what are popularly known as minerals. The mining man and the prospector are forced to include under this term anything that can be extracted with profit from the earth ; hence coal becomes a mineral, and every householder has learnt to speak of "mineral oil." A definition that excludes these substances must seem a little arbitrary. The mineralogist and the geologist, however, must find some ground of agreement by which they can distinguish the definite thing styled a mineral from the somewhat indefinite thing known as a rock. The term "rock" is left in its popular usage, as a mass forming part of the earth's crust, with no special shape of its own other than that imparted to it by external agents. When we examine a rock closely, we discover in it what we shall now describe as minerals.

A rock, in fact, is an aggregate of mineral particles, or of molecules that might, under favourable conditions, group themselves so as to form mineral particles. In a glassy lava individual minerals have not separated out, owing to the rapidity with which the mass has cooled; but in the stony portions of the same rock the material is completely "mineralised."

As a simple example of a typical rock, we may take a sandstone. A pocket-lens shows us that it consists of granular bodies, held together by something like a cement. If we break away the granules from one another and rub off the cementing matter, the majority of them will be seen to be clear, like pieces of glass, with no regular planes of fracture running through them. Other grains may be dull and earthy, and we can separate these from the majority by the eye and hand. The clearer grains have the common characters of transparency, irregular fracture, and a hardness sufficient to scratch glass. We may note the effect of dragging them under pressure over a glass surface. If we give them to a chemist, he will probably employ acids, to clean them better than our rough rubbing has done. If we ask for an analysis, he will record nothing but pure silica, silicon dioxide. The great part of the sandstone, then, consists of granular silica, possessing certain properties in this natural state. We may determine the specific gravity of the silica grains; it is always close on 2·65.

When we examine the well-known rock called granite, which is so often used for our city buildings, a number of grains are seen that at once remind us of those that we found in sandstone. If we crush a piece of the rock, and pick out these transparent grains, we recognise in them the characters that we previously noted. Their chemical composition agrees with that of the sand-grains. Here, then, we have a substance worthy of a distinctive name. It is not the dull white powdery silica of the chemist; it is silica in a mineral form, and has long been known by the name of quartz. In some granites, such as that of the Mourne Mountains, there are hollows in which the constituents stand out more clearly than they do on an ordinary broken surface. Here the hard transparent substance, quartz, assumes a geometrical form. It is no longer merely granular, but is bounded by lustrous planes. Six-sided prisms are usually seen, each with a cap of six triangular planes, like a little tent, upon it.

In crevices in the granite, and, indeed, in those of other rocks, quartz may appear in prisms of considerable size. These "shaped stones," looking like the work of a gem-cutter, seemed to the ancient Greeks to be a hard fossilised form of ice. Hence they gave them the name *krustallos*, meaning simply "ice." This type of quartz is still known as rock-crystal; but the word "crystal" has now come to be applied to all natural objects developed in geometrical forms. We know that such forms arise when we evaporate the water in which salt or sugar has been dissolved. The salt or sugar is then said to crystallise. Water, moreover, crystallises when it forms snow or hoar-frost. The delicate spikes of these solid products of freezing develop under geometrical laws. In a snow-crystal we may realise that the external form depends on a structure that runs through the whole individual; for the crystal is often a mere skeleton, a sort of plan that remains to be filled in, with hollow spaces between its regularly grouped bars.

Silica, then, may possess another character, that of crystalline form. The ease with which good rock-crystals can be obtained made them early objects of study. Nicolaus Steno, the Danish philosopher, showed in 1669 that the angles of their prisms were formed with perfect regularity, and always measured 120°. He also proved that the planes of rock-crystal occurred in pairs, the members of which were parallel one with another.[1] In time it became recognised that other natural substances crystallised in distinctive forms.

This fact suggests itself when we go back to our granite rock. A dull substance is there present, which often has an approximately rectangular form, something like a brick. A flaky shining substance, evidently quite a different thing, commonly crystallises in hexagonal plates, and is one of the most striking features of ordinary granite. Our chemist will assign to each of these materials a special chemical composition.

---

[1] On this and other points in the history of Mineralogy, see the excellent "Guide to the Mineral Gallery of the British Museum (Natural History)," obtainable from the Museum, price 3*d*.

At the outset, then, chemical composition seems to be the most fundamental character by which we can discriminate between the constituent minerals of rocks. But it is not absolutely fundamental, and no one character can be considered as determinative by itself. We are, for instance, soon met by the fact that there are two varieties of "calcareous spar," a colourless crystallised material that, like quartz, often occurs in the veins of rocks. Both forms consist of calcium carbonate; but the specific gravity of the common variety is 2·72, while that of a rarer variety is 2·94. The crystalline forms of these two varieties are also distinct. We must be prepared, therefore, to regard these substances as two separate minerals; they are called respectively Calcite and Aragonite. It may now be well to define a mineral.

aCO_3

A mineral is a natural inorganic substance with a definite chemical composition, or a composition varying in different specimens only by a recognised series of chemical replacements. *Under favourable circumstances it assumes a characteristic crystalline form.*

The above reservation as to chemical composition is introduced, owing to the impossibility of establishing a new species for every degree in which one element may be substituted for another in the construction of a mineral. The dull brick-like substance in our granite will serve to bring this point before us. Its mineral name is Orthoclase, and it is a member of an important group, the felspars. Orthoclase is a silicate of aluminium and of an alkali element, which is mainly potassium. Some specimens contain nearly 16 per cent. of potash, while in others soda replaces the potash, until the latter is reduced to 8 per cent. Yet the other characters of the mineral, if they have varied, have done so in a very slight degree. We must use our judgment as to where we shall mark off a new mineral species, distinct from orthoclase. The felspar in which soda takes the place of the whole of the potash possesses very different crystalline characters, and receives the name of Albite.

spars
orthoclase
↓
Albite

On the other hand, there is a silicate with the same composition and specific gravity as orthoclase which assumes a slightly different crystalline form; the resulting mineral is known as Microcline, and every chemical variety that we admit under the head of orthoclase has a corresponding variety in the microcline series. Here again we see the importance that must be attached to crystalline form. [illegible]

The precise measurement of crystal angles demands, however, skill and experience. We have, moreover, to find our crystal, and its faces must be satisfactorily developed. Fortunately, such slightly differentiated cases as those of orthoclase and microcline are rare. Calcite and aragonite, as we have seen, can be separated by their specific gravity. A few simple tests, indeed, serve to identify the majority of common minerals. Many rocks are built of silicates, and these, in their mineral forms, offer the greatest difficulties; but here optical tests may frequently be employed, and the microscope now enables us to determine the characters of very minute grains.

Even where a mineral particle possesses no regular external form, it may exhibit characters that prove it to possess crystalline structure. Optical tests are here the safest guide, and in this way we may become assured that sand-grains have all the structural characters of rock-crystal. Frequently a crystalline mineral, owing to its internal structure, breaks along certain parallel planes or series of parallel planes. This feature, known as cleavage, is well seen in calcite, and fractured particles are quite as serviceable in the determination of this mineral as are crystals with complete external form. To put the matter technically, every *crystallised* mineral substance is *crystalline* throughout. The amorphous or non-crystalline condition is usually only a temporary stage, or represents development arrested through unsatisfactory circumstances of growth.

The Modes of Origin of Crystals.

In laboratory experiments, crystals can be produced in three ways. The substance may be in solution and may be caused to crystallise by the evaporation of the solvent, or by precipitation through the introduction of another substance into the solution. Interaction may take place between two substances, and a new compound may be thrown down in a crystallised state. In all such cases, crystallisation has taken place from *solution*.

Some substances, as iodine, can be volatilised, and deposit themselves on cool surfaces in crystalline forms. Gases, moreover, may interact with one another, and crystalline sublimates may result. In such cases, crystals have been formed from *sublimation*.

Fused products frequently give rise to crystals on freezing, that is, on solidification. If the mass is complex, successive substances may separate out from it in a crystalline state, the order of crystallisation being regulated, not only by their respective melting-points at particular pressures, but also by the proportions in which they exist in the molten mass In such cases, crystallisation has taken place after *fusion*.

In the rocks of the earth's crust, the same three processes have contributed to produce crystallised minerals. Rock-salt and gypsum, and the quartz of veins, have commonly arisen from materials in solution. A number of metallic minerals in veins have been deposited from sublimation, just as stibnite (antimony sulphide) may be sublimed as a whole in a glass tube and redeposited at some point farther from the heating flame. Gaseous "mineralisers," such as hydrofluoric acid, doubtless assist greatly in bringing up substances from below, and in aiding their penetration through rock masses. The great bulk of minerals in igneous rocks, that is, rocks that once were in a molten state, have developed direct from fusion; but the presence of liquids and gases in such rocks complicates the question, and in many cases the molten rock may be regarded as a hot aqueous solution.

The imitation of these processes on glass slides under the microscope affords observations of the greatest interest to the chemist or the mineralogist. The development of crystals from fusion can be pleasingly studied by melting a drop of candle-grease between two glass plates and watching, between the crossed nicols of the polariscope, the growth of doubly refracting needles as it cools. Michel Lévy and other workers have reproduced by fusion in the laboratory a number of igneous rocks, with their characteristic crystallised minerals.

Minerals of *metamorphic* origin have still to be considered. When rocks come under the influence of great earth-pressures, and still more when they are invaded by molten masses deep down in the crust, a stimulus is often given to their constituents, and substances enter into combination to form minerals that were not previously present. The calcium silicate wollastonite arises thus in limestone; mica and andalusite appear in argillaceous rocks; hornblende develops, often on a bold scale, in metamorphosed igneous masses. "Mineralising agents," hot gases or liquids, spreading from a molten invader, doubtless promote this crystallisation, and also import materials into the invaded rock. The occurrence of fluorides and borosilicates illustrates such action, and we find in cases of "contact-metamorphism" a combination of materials brought in by sublimation, or in solution, with others already existent in the mass that is attacked. In other cases, pressure alone may lead to the production of certain mineral combinations,[1] which are denser than their representatives under ordinary conditions. The complex processes of change that we style metamorphic are responsible for crystal growth over hundreds of square miles of country.

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[1] Weinschenk calls this process *piezocrystallisation.*

CHAPTER II

COLOUR, HARDNESS, SPECIFIC GRAVITY, AND OTHER PHYSICAL CHARACTERS OF MINERALS

Colour

COLOUR is one of the most attractive characters of minerals, and is of considerable service in distinguishing between metallic ores. Malachite, the common copper carbonate, is always green; pyrite, iron disulphide, is brassy yellow; galena, lead sulphide, is grey. Native elements have, as a rule, colours that are constant, such as the red of copper; but several elements can only be classed together as tin-white. Chemical composition cannot be correlated with colour, since carbon in the form of diamond is colourless, and in the form of graphite is absolutely black. Most white minerals, if we exclude those that are metallic white, occur also in transparent colourless forms. Their whiteness is commonly due to internal reflections from the surfaces of cavities or of impurities, such as arise from the inclusion of foreign bodies or from the development throughout the crystal of products of decay. Impurities or staining materials, moreover, may produce various colours in minerals that are by nature colourless, just as glass can be coloured for decorative purposes. The same mineral may thus appear in a great and puzzling variety of coloured forms. Fluorspar (calcium fluoride) is a well-known instance. Here the colourless type is rare, and the violet variety styled in Derbyshire "blue John" is extremely common. Green, yellow, and red fluorspars occur, and under the microscope the colour is seen to be distributed in irregular patches through the crystals.

Coloured varieties of colourless minerals have often received separate names. Amethyst is thus merely a violet form of quartz; amazon-stone is a green microcline; ruby and sapphire are, to the mineralogist, coloured varieties of corundum, both alike composed of alumina in a crystalline form. But the subject of colour in such minerals possesses considerable fascination. Artificial corundum has been stained red by chromium fluoride and by potassium bichromate; but varying amounts of chromium fluoride have given rise to blue and green varieties. Sapphire has been imitated by introducing cobalt oxide; but it is not in the least likely that any of these substances are responsible for the colour of the natural gems. Experiments with the rays emanating from radioactive substances have shown that colour may in some instances be due to external influences. We are still far from realising why sulphur is yellow both in its natural crystals and in the laboratory, while zinc oxide is white in the laboratory and bright orange-red in its mineral form, zincite. We are not helped if we attribute the colour of zincite to admixture with small quantities of manganous oxide, which by itself is green. We may attribute the blackness of certain garnets to the presence of ferric iron; but how are we to account for the clear red of pyrope, another species of garnet, which is a compound of the colourless materials silica, magnesia, and alumina?

The true colour of a mineral specimen may be revealed only upon fracture, since a superficial tarnish may have formed upon it. This surface-film may sometimes produce a beautiful *iridescence*, as in the case of "peacock copper ore," a form of copper pyrites. Or it may amount to a crust which effectively disguises the mineral, as when cuprite, the red cuprous oxide, alters externally into malachite, or when pyrite rusts into the hydrous oxide, limonite. In such cases, a residue of unaltered material is usually found inside. Some few substances are best known in a tarnished form. The copper and iron sulphide known as bornite is recognised by its purplish iridescent colour, but is brown-yellow on fractured surfaces.

Iridescence may also be produced by diffraction-effects within a translucent mineral. The colours of thin films are often seen in quartz, owing to flaws into which air has crept.

In "precious" opal, the justly valued play of colours is due to differences of refractive index in the irregular layers of which this non-crystalline mineral is built up. A striking play of colours is seen in some specimens of felspar, as in the soda-orthoclase of a syenite from southern Norway, now much used for building, and still more notably in the labradorite of St. Paul's Island, Labrador; this iridescence arises from the grouping of minute platy substances in regular planes throughout the crystal. When the plates that cause the reflection of the light are comparatively large, a shimmer of pearly grey or bronze colour is seen on turning the specimen in the hand. When the plates are very small and thin, brilliant interference-colours are obtained. J. W. Judd[1] has shown that the development of these plates is connected with chemical changes along planes in the crystal where solution most readily takes place, and he has styled the process *schillerisation* (Fig. 1). The pyroxene known as hypersthene is sometimes "schillerised," and that called diallage owes its distinctive sub-metallic lustre to the same internal disease, schillerisation.

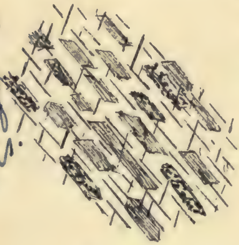

FIG. 1.—Schiller-plates in thin section of labradorite felspar. × 75.

ying or
ps = diff
n colours.

The colours of minerals when light is transmitted through them to the eye are best dealt with under the head of optical characters.

Relative Transparency.

Minerals differ greatly in the facility with which they transmit light, and many metallic minerals are opaque in all available specimens. The well-known fact that gold may be beaten so thin as to transmit a greenish light makes us hesitate to regard any substance as inherently opaque. Magnetite has never been rendered translucent; but chromite, in which chromium replaces some of the iron, transmits deep red rays when ground extremely thin. Quartz and the felspars are

d
green

---

[1] "On the Tertiary and Older Peridotites of Scotland," *Quart. Journ. Geol. Soc.*, **41** (1885), 383; and *Min. Magazine*, **7**, 81.

feldspars are not opaque

probably equally transparent in fresh specimens; but quartz remains unaltered, while the felspars undergo chemical changes which produce new minerals throughout their mass. Hence quartz in rocks is commonly transparent, while the felspars seem opaque. A thin flake of felspar, however, usually transmits some light, and the mineral, unless completely decomposed, is colourless and transparent in thin sections prepared for the microscope. The thickness of these sections may be regarded as from one-twentieth down to one-thirtieth of a millimetre.

Common mineral sulphides are opaque. Oxides of different metals vary greatly, as may be seen by comparing quartz (SiO_2) with pyrolusite (MnO_2). Carbonates, silicates, phosphates, and sulphates appear to be intended by nature to be transparent, and most of them, moreover, have colourless varieties.

Lustre.

The reflection of light from the surface of a mineral produces the effect known as "lustre," a character that can be appreciated only from an inspection of actual specimens. The two commonest lustres are the *glassy*, or *vitreous*, of which quartz gives an example, and the *metallic*, as seen in pyrite or galena. Some minerals resemble gum, and have a *resinous* lustre; others have a high type of vitreous lustre, seen in the diamond, and known as *adamantine*.

Pearly lustre occurs where divisional planes or minute inclusions allow of the reflection of light within the crystal, while *silky* lustre, as seen in fibrous gypsum, is also due to structure in the mass. The individual fibres in a "silky" mineral commonly have vitreous lustre.

In some minerals with vitreous lustre, schillerisation (see p. 10) may produce an almost metallic shimmer on certain planes. The lustre is then described as *sub-metallic.*

Tenacity.

Minerals may break readily under the hammer, being *brittle*, or may flatten and spread out into plates, being *malleable*. Pyrite is brittle, gold is malleable. Minerals that can be cut with a knife are described as *sectile.*

Flexibility and Elasticity.

A few minerals, such as native copper and the silicate talc, can be deformed by bending, without springing back into their previous shape. Such substances are merely *flexible*. When, however, like mica, they resume their shape on release, they exhibit *elasticity*. Some minerals, not ordinarily flexible, become so when developed in elongated capillary forms (p. 20).

Hardness.

This is one of the most fundamental characters of minerals in a crystalline state. While colour may have appealed to the eye of both the male and the female among prehistoric observers of minerals, the male soon found in hardness a very desirable feature. The hard mineral flint, with its broad curving surfaces of fracture, became the natural material for weapons wherever it could be found upon the globe. It was long before it was replaced by bronze, and some primitive peoples, in these days of world-wide trade, have only recently passed directly from the age of stone to that of steel.

The relative hardness of minerals can be ascertained by pressing a sharp point or edge of one of them against the smooth surface of another, and dragging it over the surface to see if a scratch is made. A powder of one of the minerals appears on the surface; we wipe this away, and examine the place where it lay with a pocket-lens. If there is no scratch, the mineral used for pressing was the softer.

Care must be taken that no foreign substance projects from the latter, such as an included grain of quartz, which will produce a scratch on almost any common mineral. Where the mineral to be tested occurs in very small crystals, pieces of it may be pressed between two plates of glass, or between the flat surfaces of two steel knives, or between a knife and a plate of glass, and its hardness in regard to these substances can be readily ascertained.

The relative hardness of minerals can be determined by instruments styled *sclerometers*, the principle of which is that, when an abrading point is drawn across or bored into a mineral surface, under a given load acting for a given time, the amount of powder produced is a measure of the hardness. The specimen must be a reasonably small one, and is first weighed; the powder is carefully washed or brushed away after the experiment, and the loss of weight is determined. By such instruments it has been shown that hardness varies in some minerals according to the crystalline face selected; all faces of what we shall describe as one crystalline form possess, however, in a given mineral the same hardness.

Experiments involving the production of scratches on the same face in different directions show, however, that hardness may be greater in one direction than in another.[1] A striking example occurs in kyanite, where the hardness on the face known as the macropinacoid is nearly double in one direction what it is in another approximately perpendicular to it.

Where a mineral possesses regular planes along which it breaks when struck (cleavage), the hardness, for determinative purposes, should be tested across the edges of these cleavage-planes or on a face produced by cleavage. Where the specimen consists of a mass of fine parallel fibres, it is best to determine its relative hardness by using it to scratch materials the hardness of which is known.

For rough and ready tests, and without any pretence to numerical accuracy, the German mineralogist, Friedrich Mohs, in 1820, arranged a number of familiar minerals as a *Scale of Hardness*, beginning with the softest.

1. Talc.
2. Gypsum. Thumbnail
3. Calcite.
4. Fluorspar. Knife
5. Apatite.
6. Orthoclase.
7. Quartz.
8. Topaz. Scratch glass & a Knife
9. Corundum.
10. Diamond.

---

[1] See for these and other delicate operations, A. E. Tutton, "Crystallography and Practical Crystal Measurement" (Macmillan & Co.).

Each member of this scale will, of course, scratch all those below it. Minerals with a hardness from 6 to 10 will scratch glass and an ordinary knife. A steel file scratches orthoclase, but not quartz; *any mineral scratched by a pocket-knife has a hardness of* 5·5 *or less.* The thumb-nail scratches minerals with a hardness of 2·5 or less; it thus discriminates simply between calcite and gypsum, two colourless calcium salts of similar aspect. After a few experiments on members of the scale, the hardness of minerals below 6 may be determined by the use of the pocket-knife and thumb-nail only. Powder, as already noted, must always be brushed off, and the surface should be examined with a lens. Minerals as hard as 5·5 may both scratch the knife and be just scratched by it. The knife leaves a trace of its steel on minerals of greater hardness, and this affords a very useful indication.

If a mineral is to be compared with those forming the scale, it should be pressed across the surface of each member, beginning with corundum, until one is found which it will scratch. In this way the members are preserved from unnecessary injury. When a scratch has been produced, the member of the scale is drawn across the mineral that is to be tested. If mutual scratches are produced, the two may be regarded as being of the same hardness; in such a case the scratches are likely to be very trifling. If the mineral lies between two members, its hardness is denoted by the whole number of the lower member and a decimal. With Mohs's scale no nearer result than ·5 can be relied on.

Though the actual figures recorded by sclerometers for the members of the scale differ with the observer, it has been proved that calcite is about seven times as hard as gypsum, while apatite is only twice as hard as fluorspar. A much greater gap occurs between corundum and topaz than between topaz and quartz, and Mohs's scale is of course imperfect, from the point of view of either geometrical or arithmetical progression. But it has the great merit of providing a convenient reference-series.

Streak.

The powder of a mineral is seen during experiments on hardness, and its colour may be observed by crushing the mineral on a clean white surface. If a knife-blade is wiped on a surface of good white notepaper, to prove that it is truly clean, and is then used to press out on the paper the fragments of a mineral which it abrades, the powdered mineral forms a coloured mark. This is technically called the *streak*. Graphite (black lead) is so soft that, as used in an ordinary "lead" pencil, it reveals its streak when lightly pressed on paper. The streak of minerals harder than the knife, such as pyrite, can be shown by the above simple method, provided they are brittle. Streak, however, is far better seen if the mineral is drawn across a surface of unglazed porcelain, such as the bottom of a saucer-shaped palette or a crucible. Streaks of metallic minerals can usually be cleaned off from such a surface by hydrochloric acid.

In this way a useful character of minerals is revealed. The two red silver ores, pyrargyrite and proustite, turn dull and almost black after exposure to light; but the former has a purple-red streak, while that of proustite is scarlet-vermilion. Hæmatite (Fe_2O_3) has a purple-red streak, though well-crystallised specimens appear black. Alabandine (MnS) is a deep-greyish mineral with a greenish streak. The brass-yellow pyrite gives a streak that is almost black. In all cases we may regard the streak as the essential colour of the mineral, masked by conditions of closer aggregation of the particles in the unbroken crystal. The high metallic lustre of a mineral like pyrite or crystallised hæmatite is lost on powdering, and this character of the surface of the crystal, whether we view a surface of fracture or a crystal-plane, appears to have a powerful effect on the colour realised by the eye. Transparent minerals with vitreous lustre yield, as is well known, a powder that appears white to the eye. Their streak is white, owing to the immense number of reflecting surfaces produced, lying at all angles with one another.

Streak is essential colour of a mineral -

Specific Gravity.

The specific gravity of a crystalline mineral, conveniently determined to the second place of decimals, is of immense service in discrimination. Pure specimens must be selected, that is, specimens externally clean and free from inclusions or from decomposition-products. When grains are being tested, they can be picked out with a moistened brush from a number placed on a glass slip beneath the microscope. Meerschaum, which must be powdered before determination, has a specific gravity of only 1·5; gold may rise as high as 19·3, and a native alloy of iridium and platinum reaches 23. But the range of specific gravity in common minerals is from 2 to about 7, and the typical rock-building species range from 2 to about 4. The mineral silicates in rocks mostly lie between 2·5 and 3·5, and, as above hinted, the second place of decimals is of service in determining closely allied members of a series.

Geologists have found it important to add certain methods to those commonly used for determining specific gravity. The chemical balance serves for many specimens, while granular substances can be placed in the specific-gravity bottle or pycnometer, very delicate forms of which have been specially introduced. But it is sometimes undesirable to break up a specimen that is too bulky for an ordinary balance. On the other hand, many minerals present themselves, in critical examples, as small crystals or grains, and only two or three of these small objects may be available.

In the former case, *Walker's Balance*, which was intended originally for rock-fragments, is very serviceable.[1] A steel bar, about 2 feet long, is provided with a cross-bar, filed on its under side to a knife-edge, and set about 3 inches from one end. The longer part of the bar is graduated into inches and tenths, or centimetres and millimetres, from the point vertically above the knife-edge outwards. The knife-edge rests on a support, and the bar can turn about it like a lever. A suitable weight is hung from the shorter part of the bar, by a metal loop which fits into notches, so that it can be adjusted to various distances. An upright carrying another metal loop is placed at the end of the long part of the bar, the bar being passed through the loop, so as to catch in it if the weight is temporarily hung too far from the fulcrum. A mark should be made on this loop to show the position of the bar when horizontal. In this position it should swing freely (Fig. 2).

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[1] Described by W. Walker, *Geol. Magazine* (1883), 109. Made by G. Lowdon, Reform Street, Dundee, price 31*s*. 6*d*.

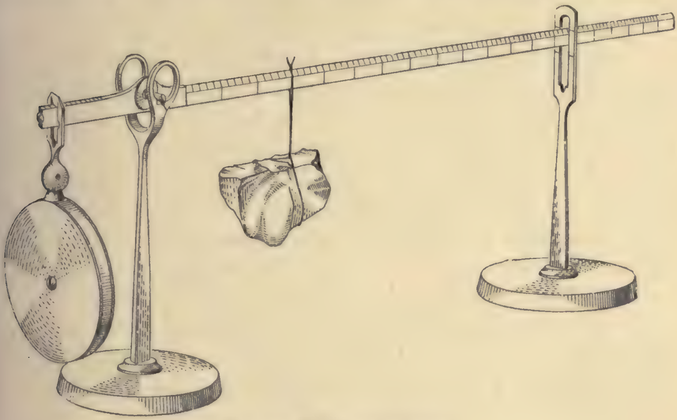

FIG. 2.—Walker's balance.

The specimen, which may measure an inch or more each way, is hung by a cotton thread from the graduated part of the bar, so that it can be easily slid along it. When several specimens are to be determined, a simple loop like that figured serves well, and the ends of the thread at the top enable one to shift the specimen without touching the bar. Between each determination, the loop should be dried with a handkerchief. The constant weight and the specimen are arranged so that the bar balances horizontally with the specimen somewhere within the first 5 to 8 inches of the scale. The reading indicated by the point of suspension of the specimen is the reading in air, *a*, and can be easily given to two places of decimals, even where millimetres are used as a scale. The specimen, still suspended, is then placed in a tumbler of water, brushed over for the removal of air-bubbles, and shifted along the bar until horizontal balancing again occurs. The constant weight has been carefully kept in its former position. The reading now obtained with the specimen completely immersed in water may be called *b*. It is clear that the two readings are inversely proportional to the weights

Wt in air = a Reading in H_2O = b

in air and water respectively. Hence the specific gravity $G = \frac{b}{b - a}$. $y = \frac{b}{b-a}$ $\frac{b}{b-10} = 6$

Walker's instrument is sold packed in a box for travelling.

R. Smeeth[1] has obtained the specific gravity of small specimens as follows: A chemical balance is arranged in the usual way, that is, with a counterpoise and hook on one side in place of the ordinary pan. A small pan containing vaseline is hung by a silk thread from the hook. The weights of this pan, in air and water, are determined (m and n). Several small crystals or grains of the mineral are laid on the vaseline, and their weight in air is found by deducting m from the new reading. The vaseline is then warmed, and they sink into it; when cool, the pan is immersed in water, and the difference between its weight in water n and that now found gives the weight of the grains in water. The object of the vaseline is to prevent flotation of the grains.

E. Sonstadt,[2] however, showed, in 1874, how dense liquids can be used for determining the specific gravity of small gems, and, indeed, of objects that can hardly be examined without a lens. If we immerse these in a liquid, anything that floats on its surface, after having been thrust down into it, is of less density, while anything that sinks to the bottom is of greater density. If the object neither sinks nor floats, but remains, as it were, suspended in the liquid, it has the same density as that of the liquid. The latter density can be determined by a balance, with a weight at one end of the beam that can be sunk into the liquid, far more accurately than we can determine the weights in air and water of a minutely granular mineral. Hence we may find, from experiment on the liquid, the specific gravity of the grain. The density of the liquid, moreover, may be determined by dropping into it glass beads or mineral fragments of known density, until one is found that remains suspended within the liquid.

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[1] *Sci. Proc. Roy. Dublin Soc.*, **6** (1888), 61.

[2] *Chemical News*, **29** (1874), 128. For details as to the development of this method see various petrographic text-books; also G. Cole, "Aids in Practical Geology," pp. 29–32.

The difficulty lies in finding transparent liquids of sufficient density for practical use. Sonstadt's original liquid, a solution in water of potassium and mercury iodides, is corrosive and poisonous, and has been generally superseded by an aqueous solution of *cadmium borotungstate.* This, however, acts chemically on carbonates. *Methylene iodide* is more convenient, and has a maximum density of 3·33. This may be raised to 3·65 by dissolving iodoform in it, and afterwards iodine.[1] It is diluted with benzene, not with water, and darkens on exposure during some hours to light. It resumes its clear yellow colour when a little mercury is shaken up in it to remove the iodine that has separated out.

Bromoform, which gives a maximum density of 2·84, is also used. It is cheap, and may be diluted with ether or benzene. The great advantage offered by methylene iodide and bromoform is the absence of crystallisation as they are concentrated.

The practical use of all these liquids was immensely facilitated by a discovery made by W. J. Sollas in 1891. If a dilute solution of the liquid is allowed to stand for some twenty-four hours on a column of the liquid at its maximum density, diffusion takes place slowly. Hence a column is obtained the density of which increases downwards, and differences of density at different levels are manifest even after three or four days. The liquid can then be evaporated down to its maximum density, and is available for further use.[2]

If Sollas's *diffusion-column* is established in a test-tube, fragments of minerals of known specific gravity, say between 2·5 and 3·2, can be dropped into it, and these will remain suspended at the levels where the liquid has the same density as themselves. The grains the specific gravity of which has to be found are dropped in also, and their position in vertical relation to the index-fragments can be measured by holding a millimetre scale against the side of the test-tube and reading off the distances direct. The value of a unit on the scale is found from the distance separating two index-fragments. T. D. La Touche has shown how the instrument may be conveniently fitted with a fixed scale, a sliding frame carrying a horsehair, which passes across a mirror, being used to assist in reading off the position of the grain (Fig. 3). The specific gravity of very minute mineral grains can thus be determined very accurately to the second place of decimals. The importance of the diffusion column in geological research, where small felspars and so forth have to be identified in powdered samples of rocks, cannot now be overrated.

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[1] J. W. Retgers, *Neues Jahrb. für Min.* (1889), **2**, 185; and *Min. Mag.*, **9** (1890), 46.

[2] Sollas, *Nature*, **48** (1891), 404; La Touche, *ibid.*, **53**, 199.

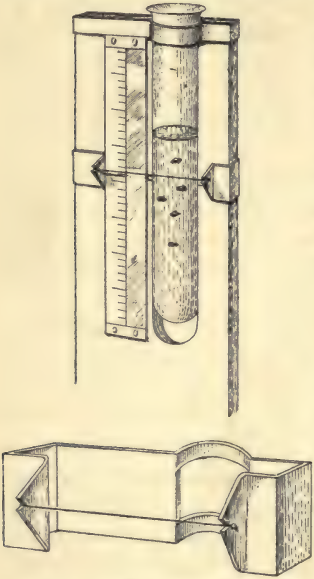


FIG. 3.—Diffusion-column (after T. D. La Touche).

Taste.

Minerals soluble in water usually have suggestive tastes. It would be of little advantage to examine all the specimens in a large collection with the tongue; but, when appearances seem favourable, rock-salt, the alums, or melanterite ($FeSO_4 \cdot 7H_2O$) may be tested in this simple manner.

Mode of Occurrence and Aggregation.

Crystals of certain minerals are liable to assume a *habit* in which they commonly occur. They may exhibit flat and *tabular* forms; or they may be elongated in a particular direction, which is often that of the axis of a prism of the system in which they crystallise. Such elongated forms may become needle-like or *acicular*; when still longer in proportion to their cross-measures, they resemble hairs and become *capillary*. Millerite (NiS), for instance, is commonly found in the cavities of veins in delicate brass-yellow hair-like crystals. Capillary types may be produced by the excessive elongation in one direction of forms that are not prismatic from the crystallographic point of view. Even minerals of the cubic system (p. 64), such as chalcotrichite, a variety of cuprite, may yield capillary rods. Native silver, another cubic mineral, develops in twisted masses, like bunches of string, which enable it to be recognised on the walls of mines. Native copper sometimes adopts this habit.

Crystals greatly elongated in one direction, so as to become rod-like or even capillary, are often aggregated in parallel growths, thus building up a *fibrous* mass. This feature is hardly characteristic of particular minerals, but is often seen where crystallisation has taken place across an open crack. Chrysotile (fibrous serpentine) and asbestos (fibrous amphibole) develop thus, and their flexible fibres are of commercial importance. "Satin-spar," with its beautiful silky lustre, is either calcite or gypsum in a fibrous mode of aggregation.

When a mineral is deposited between two nearly fitting layers of rock, it is liable to spread out in a filmy form, branching in various directions, and ultimately resembling a vegetable growth. Such aggregates are styled *dendritic*, and are very commonly mistaken for fossil seaweed or mosses. They are frequently produced by black manganese oxides spreading along crevices or bedding-planes. The green inclusions in "moss agate" are dendritic growths of a more bunchy type; the mineral in this case is usually the silicate chlorite. Such "dendrites," which have developed freely into some cavity, connect the structure with more considerable branching growths.

When a crystalline mineral occurs as an aggregate of crystals which have grown against one another without regular boundaries, it is said to be *massive*. Quartz in veins is commonly massive; calcite is massive when it makes the rock called marble. The individual crystal in such cases is sometimes said to be *anhedral*, because it has no good bounding planes, in opposition to the well-crystallised or *euhedral* forms. A

$CaCO_3$ — calcite — marble.

mineral filling up spaces between others and receiving its form from them is said to be *allotriomorphic*; it has a form that is not its own, in opposition to the *idiomorphic* (or euhedral) type. Such terms may easily be multiplied by those who find technical language a convenience rather than a hindrance.

Massive minerals, by their mode of assemblage, may assume a somewhat regular external form. *Concretionary* action, by which mineral material becomes deposited or concentrated in a rock round certain centres, leads to the formation of spherical or ellipsoidal masses. In a bedded rock, the mineral substance collects most easily along the planes of bedding, and the resulting concretions are in reality parts of the rock locally cemented by the matter that has come together. The planes of bedding are often recorded on the exterior of the concretion, which tends to split along them when struck. Ellipsoidal forms have their shortest diameters perpendicular to the bedding, and two or three concretions often coalesce, producing fantastic groups. The concretion is a rough attempt at crystallisation, and sometimes the mineral succeeds in grouping itself in radial fibres about the centre whence it began to grow (Fig. 80). Fossils often serve as centres in calcareous shaly rocks. Concretionary growth on a small scale produces bodies like peas (*pisolitic* structure), or like the eggs of fish (*oolitic* structure). These may occur when material is deposited around minute particles of rock in hot springs, seas, or lakes. Calcium carbonate is thus laid down round mineral grains and fragments of shells, and the cementing of the mass forms the well-known oolitic limestones, the type of which is Portland stone.

In glassy volcanic rocks, and also in artificial glass, silicates often develop in spherical concretions known as *spherulites*. These may have a radial structure, and are sometimes concentrically zoned, owing to interruptions in their growth. Though they are usually small, as in the glassy lava of Lipari, they may be found measuring a metre in diameter. Spherulitic structure always represents hurried and imperfect crystalline growth.

Concretions that have interfered with one another, or which have been deposited on a flat surface as a succession of encrustations, produce a surface of undulating rounded bosses, which is said to be *mammillated*. When the concretions have formed with some freedom, but still in contact, the mass is styled *botryoidal*, from its resemblance to a bunch of grapes. Chalcedony is often mammillated (Fig. 88); psilomelane, a black hydrous manganese oxide, is often botryoidal (Fig. 82). Chalcedony – mammillated.

Where a solvent, such as water containing carbon dioxide in a limestone cave, drops slowly from a height, evaporation may cause a deposit of the material dissolved. Tubular aggregates thus arise, the solvent draining out down the centre. Ultimately the tube may become choked, and the mass becomes thickened by the solvent flowing down over its surface. A massive mineral thus deposited is *stalactitic*. up Some of the dissolved substance is carried to the ground below, and there forms mammillated films, known as *stalagmite*. down The stalagmite sometimes rises, through continued deposition, until it meets the stalactite, and a perfect column is produced from roof to floor. The growth is usually slow enough for the formation of fibrous aggregates, the fibres radiating from the original central tube of the stalactite. Pauses in deposition may be marked, as in a spherulite, by concentric structure. A delicate combination of these structures causes polished specimens of stalagmitic barytes (barium sulphate) from Derbyshire to pass as fossil wood.

Stalactites of calcite may be studied in all stages under almost any railway-arch, where water is dripping through the mortar. Each stalactite is sometimes a single tubular crystal, as may be seen by its regular cross-fracture along uniform planes of cleavage.

Crystalline material may sometimes be deposited stalagmitically on the surfaces of pre-existing crystals, which thus become coated over with a cap or a continuous crust. The pre-existing crystal may be broken away or even dissolved out by natural processes, and the cap or crust remains as an *epimorph*, an aggregate that has derived its form from that on which it was deposited. Epimorphs of quartz often occur on cubes of fluorspar or on conical crystals of calcite.

Pseudomorphs are more puzzling. These are replacements of one mineral by another without the destruction of the original external form. A simple case is where limonite ($H_6Fe_4O_9$) replaces pyrite (FeS_2). The cubical form remains; but the sulphur has oxidised and gone off as H_2SO_4, and the residual iron has taken up oxygen and water and has passed into compact brown iron rust. Sometimes the pseudomorph retains nothing of the original mineral. Silica, as chalcedony, thus replaces cubes of fluorspar; pyrite may replace the calcium carbonate of fossil shells.

At times we find a mineral, without change of chemical composition, settling down into a state that is more stable, under existing conditions, than that which it previously assumed. Aragonite thus passes ultimately into calcite, though the change may in nature be retarded through long periods of geological time. When heated in a Bunsen flame, however, the change takes place while the crystal of aragonite flies to pieces. Since the specific gravity of aragonite is 2·94 and that of calcite is 2·72, an expansion of the material present must take place. The pyroxenes, again, pass in time into corresponding amphiboles, sometimes pseudomorphically, but usually with a change of outer form. In cases where no chemical change is traceable, but where a distinct mineral species has arisen by a process of molecular rearrangement, the later mineral is said to be a *paramorph* of the earlier.

Pyrite cube = Limonite cube
Pseudomorphs

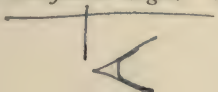
Aragonite — calcite

30 ✓
50 ✓
50
25
1.75

CHAPTER III

COMMON FEATURES OF CRYSTALS

We have already stated that crystals are bounded by plane surfaces. These are the *crystal-planes* or *faces*, which must be considered as stretching out in all directions, with no form or boundaries except those imparted to them by intersection with other faces. From our geometrical studies, we are apt to think of a pyramid face as triangular and a prism face as rectangular; but in crystals these planes are so named on account of their relations to certain reference-lines, and their forms depend entirely on the occurrence of other planes of a similar or dissimilar kind. The intersections of crystal-planes produce *edges*. A particular line within the crystal may be selected, on various grounds, as one to be placed upright for the appreciation of the crystal. Edges may be found converging, probably both above and below, towards this line. The lines of longitude on a globe converge towards the poles, and, similarly, the two ends of the selected vertical line in the crystal may be regarded as poles, and the converging edges may be styled *polar edges*. A double pyramid, formed of two similar pyramids joined base to base, has two series of polar edges, in regard to which the edges of the plane of junction of the pyramids may be called *lateral*. Where three or more edges meet in a point, a *solid angle* is produced; but such angles are unimportant in the scientific description of crystals. The angles measured in CRYSTALLOGRAPHY are those made by two planes with one another. If a line is drawn on each of two faces perpendicular to the edge in which the faces meet, or to the edge in which they would meet if produced, the angle between the two lines is the *interfacial angle*. This is clearly the smallest possible



angle that can be made between two lines, one of which is drawn on one face and one on the other. If the faces are expressed by any form of notation, such as M and N, and the interfacial angle is 120° 40′, we may write—

$$M \,.\, N = 121^\circ\ 40', \text{ or simply } MN\ 121^\circ\ 40'.$$

As will be seen later, the angles between the normals to the faces are now generally given by crystallographers. Since these are the supplements of the actual interfacial angles, the angle recorded for the above planes will then be MN 58° 20′ (Fig. 4).

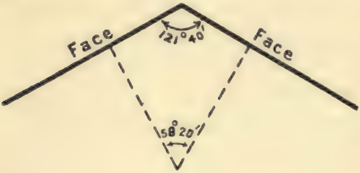
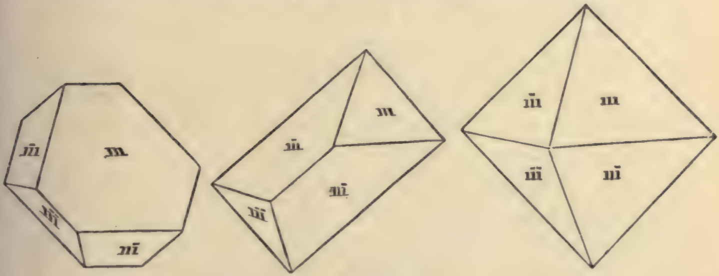


Fig. 4.

In most crystals there is an entire absence of re-entrant angles; that is, no two planes slope so as to produce a notch in the external form. Re-entrant angles, however, commonly occur in the composite crystals styled twins (p. 83). Where two or more crystals casually develop across one another, with a partial inclusion of one by the other, re-entrant angles are, of course, produced; but these have no regular relation, as they have in twin crystals, to the crystal form. *Parallel growth*, where one crystal grows up side by side with another, adherent to it, and perhaps with some planes in common, may produce re-entrant angles that are related regularly to the forms assumed.

In nature, crystal growth is impeded in many ways. Even where the crystal is developed in the midst of a solution from which it is separating out, the food-supply, so to speak, may not be equally available on all sides. Conditions of temperature may be unequal in the surroundings of the crystal; convection-currents may be set up which tend towards re-solution or resorption. Planes so developed that they correspond with one another as a crystallographic series, since they have absolutely the same inclinations to certain directions within the crystal, may yet have very various sizes. A hexagonal prism, for example, with its planes meeting in six parallel edges, and its six interfacial angles all measuring exactly 120°, may yet have no two faces truly equal. The faces, however, as Steno discovered (p. 3), occur in pairs, the members of which are strictly parallel with another. The crystallographer can take no account of the infinite variation in size that may occur among crystal-faces which are similar in their inclinations to his guiding lines. The angular measurements show him the relations of the faces. The form of the face may be suggestive, but its bounding edges may be unduly numerous, owing to the over-development of some other face that cuts across it (Fig. 5). In a crystal model or drawing all this is set right, and the crystal is supposed to have developed under ideal conditions.



(i) (ii) (iii)

FIG. 5.—Crystals of magnetite, (i) and (ii), with unequally developed faces, but representing crystallographically the octahedron (iii).

In the molten rocks styled igneous, crystals have fair chances of ideal development, since the viscidity of the mass as it cools, and as the minerals separate out, enables the crystals to remain suspended in a bath that is supplying them with additional molecules from all sides. But where a solvent, such as water, is passing through a fissure, any crystals that are deposited will probably be attached at one end, which develops no planes, but which simply moulds itself on the surface from which it springs. Crystals, however, produced by the coming together of similar molecules in a bedded, that is a sedimentary, rock have a remarkable power of thrusting aside the surrounding matter, and in consequence of attaining considerable size and well-developed crystal forms. Crystals of pyrite in slate are good examples. Their brass-yellow cubes, with sharp edges, have grown within the rock, without including any of its clayey matter. In other cases, however, both in igneous and sedimentary rocks, inclusions have been caught up, and these render analysis especially difficult.

Crystals suffer from various imperfections, besides those due to the unequal development of crystallographically similar faces. Their outward growth parallel to a single face may not be uniform over the whole surface of the face, and step-like irregularities and little upstanding platforms may result. Sometimes an edge is formed by the commencement of a new face, and then, returning to its former plan, the crystal proceeds to develop a face parallel and almost continuous with the original one. A repetition of this process produces *striated faces*, the striæ being in reality the bands formed across the predominant face by the partial development of a second series of planes (Figs. 79 and 87). By the development of microscopic steps, a face may appear curved, and the whole crystal may become strikingly deformed (Fig. 83). This *curvature of faces* is so common in dolomite as to be a characteristic feature.

Incomplete or *skeleton-crystals*, like those so often seen in snow, arise where crystallisation is hurried. Rock-salt dissolved in water and dried out again on a glass slip often produces "hopper-shaped" crystals with hollow faces, the cube having grown more rapidly at its edges than at its core. Skeletal forms are often built up of imperfectly shaped molecular aggregates, which may affect polarised light, but which must be regarded as only the beginnings of crystals. These individual bodies, globular, pear-shaped, or rod-like, have been called by Vogelsang *crystallites*.[1] The repetition of Vogelsang's experiments under the microscope, and, indeed, the artificial crystallisation of almost any salt from solution, afford the most attractive insight into the early stages of crystal-growth.

The size of crystals is limited by time and molecular supply. Given the molecules, slow crystallisation may produce crystals the dimensions of which may be measured in metres. Slow crystallisation implies a prolonged maintenance of suitable conditions. Where a solvent evaporates quickly, or where a molten mass is quickly cooled, a meshwork of small crystals, or even crystallites, alone results.

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[1] "Sur les Crystallites," *Archives néerlandaises*, **5–7** (1870–72).

A pause in the growth of a crystal often allows of the deposition of some other substance as a film upon the surface. When growth is renewed, that is, when favourable conditions have returned, this film is not an obstacle to the perfect grouping of the new molecules in continuation of the crystal already formed. No doubt a film of this kind is far from being continuous. Hence *zoning* is set up, and successive zones may arise, as if the crystal had been painted over with new material from time to time. In a section, the impurity forming the film between two successive zones may reveal itself as a colour-line or a row of specks, following the outline of the crystal. In very many cases, a change in the material supplied to the crystal produces zones, sometimes of different colours (Fig. 119, ii). In a complex silicate, one zone may contain a ferrous compound and another may contain a certain amount of the iron in the ferric state; in the still more delicate instances of colourless silicates, calcium in one zone may be represented in part by sodium in another. Though we have strong reason to believe that such zones do not reproduce precisely the same crystal-form,[1] the resemblance may be so close as to defy all but the most refined external measurements, and we may accept the final product as a compound crystal built up of layers of slightly different chemical compositions. Optical tests may reveal zoning which it is otherwise difficult to observe, since the layers of different molecular composition will have different indices of refraction. Zoning must often arise owing to the change of composition in the material from which the crystal is developing, since a particular kind of matter is being steadily withdrawn from the mixed material by the crystal.

Many crystals are able during growth to arrange any impurities caught up in them in zones. Even inclusions of glass or liquid may thus become grouped parallel to the crystal-surfaces.

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[1] See A. E. Tutton, "Crystalline Structure and Chemical Constitution" (1910), p. 194.

Inclusions in crystals may consist of stony matter, as when small crystals are shut up in a larger one; or of glass, which is a residue of the material from which the crystal was developing; or of gas, which may be detected by breaking the crystal up in a vacuum; or very frequently of liquid. *Liquid inclusions* often show a bubble on their surfaces, which moves when the crystal is inclined; the liquid has shrunk since it first occupied the cavity. The bubble may disappear on heating the crystal, and a number of beautiful experiments have been made on microscopic examples of liquid inclusions. In some cases it is clear that the inclusion results from partial solution of the crystal. In some old sandstones, where the rolled quartz grains are held together by a cement of quartz, bands of minute liquid inclusions run continuously through adjacent grains and the cement. They must, then, have arisen along certain surfaces of attack that traversed the rock in its consolidated state. The quartz of granite (p. 199) abounds in such inclusions, of quite microscopic dimensions; it is possible that they also were developed during the passage of solvent liquids through the mass after it had become crystalline.

In some crystals, such as rock-salt and even quartz, inclusions of water, with movable bubbles, may be seen with the unaided eye. The liquid, in some microscopic cases, has been proved to be carbon dioxide under pressure.

The Measurement of Crystal Angles.

Steno, in 1669 (p. 3), and Maurice Antoine Cappeler, a Swiss naturalist, in 1723, satisfied themselves as to the regular structure of crystalline minerals. But it was left to Jean-Baptiste Louis Romé de l'Isle to convince the masters of the scientific world. The great naturalist Buffon, near the close of the eighteenth century, still felt that the immense variety of crystalline forms defied classification by man. He wrote seriously, "In general, crystalline form is not a constant character, but more uncertain and more variable than any other of the characters by which minerals can be distinguished from one another." It is clear that Buffon had not personally adopted experimental methods of research.

De l'Isle was attracted towards natural studies while a prisoner of war in the hands of the English in the East Indies, and on his return to Paris, assisted by a kindly patron, he set himself to measure crystals. Correspondence with Linné helped to confirm him in his views, and he published his conclusions as to crystal-forms in two works in 1772 and 1783. The measurement of his specimens was performed with a simple form of angle-measurer or *goniometer*, devised for him by an optician, Carangeot. Réné Just Haüy, the son of a poor weaver on the borders of Picardy, had about the same time become a clerical professor in Cardinal Lemoine's college in Paris. Haüy also devoted his leisure to the study of crystals, and was the first to demonstrate the interrelations of the various forms adopted by the same mineral species. Thanks to the accurate work of these two men, who were in their own day rivals rather than co-operators, crystallography was placed on a scientific basis. To-day we find one of the keenest of our crystal-measurers able to assert,[1] "Crystallographic work has proved conclusively the truth of the law enunciated over a hundred years ago by the Abbé Haüy, that every solidifiable chemical element or compound is characterised by a crystalline form and internal crystalline properties peculiar and proper to itself, quite distinct from the forms and properties of every other element or compound."

GONIOMETRY, which is now carried to a high pitch of accuracy, has become the most refined method of analysis.

Carangeot's *contact-goniometer* (Fig. 6) consists of two flat bars, held together by a bolt or rivet, about which either can be turned, so that they move in regard to one another like the blades of a pair of scissors. A screw-clamp on the bolt holds them fast in any particular position. In measuring a crystal, the inner edges of the bars are fitted down on two selected faces, so that they lie at right angles to the interfacial edge. They are then clamped in position, and the angle between them is measured by applying them to a protractor. This angle is the actual interfacial angle, and is nowadays represented, for purposes of calculation, by its supplement.

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[1] A. E. Tutton, "Crystals their own Analysts" (*Daily Mail*, September 13, 1912); also *Nature*, **91** (1913), 521.

Many types of contact-goniometer exist, and S. L. Penfield has produced cheap forms in cardboard, which are sold by Messrs. Ward, College Avenue, Rochester, New York, at about 2*s*. each. With the aid of simple instruments such as these, and of measurements that did not profess to be accurate within a quarter of a degree, the two French observers were able to classify the immense variety of natural crystals under a limited number of groups or *systems*.

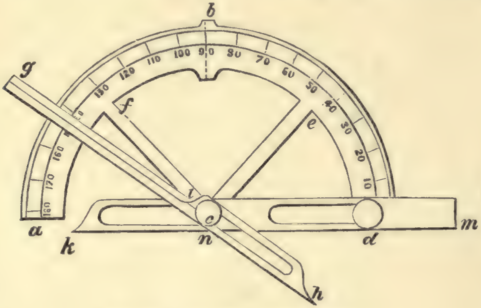

FIG. 6.—Contact-goniometer.

From what has been said about the imperfections of crystals, and the steps that may occur upon their faces, it is obvious that many specimens are unfit for goniometric work. The smaller crystals, with shorter life-histories and with bright and uniform faces, are likely to give the best results. Wollaston's *reflective goniometer* was invented in 1809 to meet this difficulty, and its principle is adopted in all modern instruments for research on crystal-forms.

If the face of a crystal, with a fair lustre, is held close to the eye and turned about, an image of distant objects can be clearly seen reflected from it. Fix such a crystal on a horizontal axis, so that an edge between two faces lies horizontally and in linear continuation of the axis. Place the eye close to the crystal, and look into one of the two faces. Turn the axis until the image of a horizontal bar, say a window-bar (called the first "signal"), appears to coincide with a horizontal mark (the second "signal") parallel with it, as seen by the eye when it looks beyond the crystal. The crystal is so small that there is no difficulty in seeing the reflection of one signal and the direct view of the other at the same time. The edge of a table, or of a book on the table, if set parallel with the window-bar, serves well as the second signal. Now rotate the axis carrying the crystal, until the reflection of the first signal in the other face coincides with the second signal. The angle through which the axis has been turned is the supplement of that between the two faces.

In Wollaston's instrument (Fig. 7), a vertical graduated circle, E, is mounted on the horizontal axis, and a vernier index, R, enables the angle to be read off. The axis carrying the circle is usually hollow, and that carrying the crystal passes through it. The crystal is fixed with beeswax in a convenient position to a small carrier, O, which is fitted with a universal joint, so as to facilitate the adjustment of the edge parallel with the axis of rotation. The graduated circle can be set at zero, and the

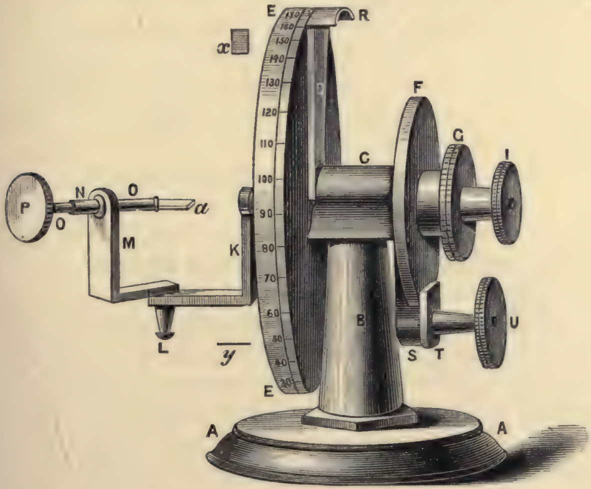

FIG. 7.—Reflective goniometer.

first face can be brought into position by rotating the internal axis, I, only. The second face is brought into the same position by rotating the tubular axis carrying the circle, the inner axis remaining fixed in it by its tightness, and the graduation may be arranged so as to give the actual interfacial angle or its supplement, the angle of rotation, as may be desired.

An instrument of this kind, with or without the refinement of the hollow axis, can be easily made by a student of moderate mechanical skill, and will give accurate readings within half a degree.[1] A marked improvement, introduced by E. Sang early in the history of the Wollaston goniometer, is the substitution for the second signal of the reflection of the first signal, seen in a dark glass mirror placed below the axis. A further improvement, made by E. Mitscherlich in 1843, is the introduction of a collimating tube, which focuses on the crystal-face the image of a slit cut in a diaphragm at its farther end. This slit serves as the signal, and the crystal is viewed through a telescope of low magnifying power, which is furnished with cross-wires. The slit is illuminated by a light placed behind it, and its image is brought, by rotating the crystal, into coincidence with a cross-wire. This method is adopted in the most delicate modern goniometers, and in these the axis of rotation, with which the crystal-edge coincides, is set vertical. The exact vertical and central adjustment of the crystal on its carrier is performed by screws, which push or pull parts of the carrier that have a rocking movement over one another. The vernier on the horizontal circle is read with a microscope, and the circle itself is of course fitted with a screw for fine adjustment during rotation.

Zones, Axes, and Symmetry of Crystals.

a ∞ 1 b 2

When careful measurements of crystals are made, it becomes clear that their faces are arranged with varying degrees of symmetry. Steno pointed out the common occurrence of planes in pairs, the members of which are parallel to one another. Sometimes this is the only feature that suggests a symmetrical structure in the crystal. A series of planes may, however, often be found parallel to one and the same line. These planes are said to form a *zone*, a term which has nothing to do with the zone-structure produced during crystal-growth. The lines with which the planes are parallel is the *zone-axis*, and the intersections of the planes of the zone are clearly parallel with this axis.

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[1] See figures and descriptions in G. Cole, "Aids in Practical Geology," pp. 17–19.

In choosing a position in which a crystal shall be held in order to read off its faces, it is usually convenient, and at the same time structurally correct, to set some zone of planes upright. In quartz, for instance, there is an obvious zone of six similar planes, forming the hexagonal prism. We set this upright, and find that in so doing we have recognised the most important structural direction in the crystal.

A plane may of course belong to two or more zones. An octagonal prism, closed above and below by planes perpendicular to its prismatic planes, provides four horizontal zone-axes, and the planes at its upper and lower ends are included in each of the four corresponding zones.

In practice, for the description of crystals, we picture three imaginary lines, called *crystallographic axes*, intersecting in a point and set up inside the crystal. Such lines are best selected for each mineral species as the intersections of three planes passing through the centre and parallel respectively to three prominent faces observable in crystals of the species.

If we call the three axes of reference X, Y, and Z (Fig. 8), a plane may cut X, Y, and Z at three equal or different distances from the centre in which these axes intersect; or it may be parallel to one axis and cut the other two. In either case, the portions cut off on the axes are styled *intercepts*. If in a mineral species we select as a type or unit some commonly occurring plane that cuts all three axes, its intercepts are styled the *parameters* of the particular species, and are designated as *a*, *b*, *c*. We can express in numbers, though we may

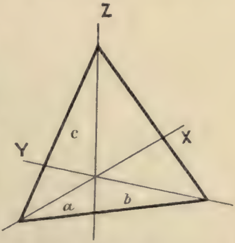

FIG. 8.

have to use several places of decimals, the ratio that exists between the intercepts. The ratio of the unit intercepts or parameters is the *axial ratio* for the species, the intercept on *b* being taken as = 1.

There is then one axial ratio for each species, though the ratio between the intercepts made by planes of forms other than the selected unit may be stated for comparison with the unit.

Any planes that possess the same series of intercepts are planes of the same *crystal-form*.

In a simple case, that of the ordinary double pyramid (Fig. 9), eight such planes occur and constitute a single form. If a plane is parallel to one axis and cuts the other two, the symbol for infinity appears in the statement of the ratio of its intercepts; if the plane is parallel to two axes, that is, if it is one of the fundamental planes by which the axes were determined, it still must cut the third axis at a distance which in all cases is expressible by the unit 1. Such a plane, under the laws that govern crystal-growth, can usually have another parallel with it, cutting the same axis at the same distance from the point of intersection of the axes, but on the opposite side of the plane containing the other two axes; these two parallel planes will constitute a crystal-form. In crystals of low symmetry, a form may consist of one plane only.

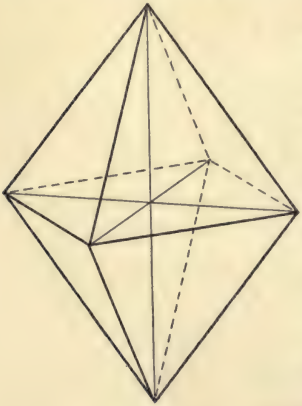
FIG. 9.

In a crystal, as we have already seen (p. 26), the planes of the same form may be of very various sizes; but their relations to one another and to other planes, as determined by angular measurements, remain absolutely precise. In a drawing or a model, the accidents of individual growth are properly disregarded, and the ideal crystal is represented; each plane in each form that is present will thus be of the same area as every other plane of the same form. That is to say, when one of these ideal crystals is referred to any system of three crystallographic axes, imagined as intersecting in the centre of the crystal, the distances cut off by planes of the same form on these axes will not merely yield the same crystallographic ratio, but the three actual measurements for one plane will be repeated for each plane of that form. Two parallel planes of a form will thus lie at equal distances on opposite sides of the centre of the ideal crystal.

Such a drawing or model displays the full *symmetry* attained by the molecular structure of the mineral species which it represents. A skilled crystallographer reads off this symmetry from the way in which his angular measurements repeat themselves and form series as he works round about the natural crystal.

From the drawing or model we realise that a crystal possesses both planes and lines as *elements of symmetry*. A *plane of symmetry* passes through the crystal so that the part of the crystal on one side of it is an exact reflection of that on the other. Cut the crystal down along the plane of symmetry, remove one half, and place the other half with the plane of symmetry in contact with the surface of a mirror. The crystal should now appear restored. In fact, a plane of symmetry must satisfy the following test. A perpendicular dropped upon it from any point within the crystal, and produced to an equal distance on the other side of the plane, must terminate at a point within the crystal. Hence every point in or on a crystal on one side of a plane of symmetry has a corresponding point on the other side, immediately opposite to it.

plane
symmet

An *axis of symmetry* is a line about which the crystal can be rotated through 180° or less, and yet at some moment or moments it will appear as if no rotation had taken place. That is to say, the crystal will present exactly the same aspect to the observer at least twice during a complete rotation. A regular hexagonal prism, rotated about its vertical axis, will present the same aspect six times during a rotation. The axis in this case is one of 6-fold symmetry. In crystals, the only

Hex. axis is 6 fold symmetry.

axes of symmetry that occur are 2-fold, 3-fold, 4-fold, and 6-fold. Where more than one plane of symmetry is present in a crystal, the intersections of the planes of symmetry will be axes of symmetry. Three planes of symmetry intersecting in one line will thus indicate an axis of 3-fold symmetry.

The laws that govern crystal-structure limit the number of types of symmetry possible in natural geometrical forms. Thirty-two *classes* of crystals have been recognised, differing from one another in the elements of symmetry that are present. These classes are grouped under seven larger heads, or *systems*, which replace the four systems adopted by the early mineralogists.

Essential Features of the Seven Crystallographic Systems.

Various authors assign various names to the crystallographic systems, and most of those here adopted have the sanction of long usage. The names of the subdivisions or classes are less important, the recognition of the type of symmetry in each class being the essential matter. It is difficult to suggest the degree of symmetry in some cases by a single adjective. When we review the classes within each system, certain essential features stand out which link them together into systems, and we may now state these features in a table.

TRICLINIC SYSTEM.

No axes or planes of symmetry.

MONOCLINIC SYSTEM.

One axis of 2-fold symmetry, and one only; or one plane of symmetry; or both. When, as commonly happens, both elements of symmetry are present, the axis of symmetry is perpendicular to the plane of symmetry.

When the axis of symmetry alone occurs, the planes developed at one end of it differ from those at the other end.

RHOMBIC SYSTEM.

Commonly, three planes of symmetry, perpendicular to one another; the intersections of these three planes are three axes of 2-fold symmetry, *which are unequal in length.* Or two planes of symmetry, perpendicular to one another and intersecting in an axis of 2-fold symmetry. Or three axes of 2-fold symmetry, perpendicular to one another, but no plane of symmetry.

TETRAGONAL SYSTEM.

One axis of 4-fold symmetry, and one only. Less commonly, three axes of 2-fold symmetry, perpendicular to one another, *two of which are equal in length.*

Extremely rarely, one axis of 2-fold symmetry and no other element of symmetry. The forms in this class are distinguished from the monoclinic forms that possess only an axis of 2-fold symmetry by the occurrence of planes of the same kind at both ends of the axis of symmetry, though no two of these are parallel to one another.

CUBIC SYSTEM.

Four axes of 3-fold symmetry (which correspond in position with the diagonals of a cube), together with three axes of 4-fold or 2-fold symmetry, which are perpendicular to one another and *equal in length.*

HEXAGONAL SYSTEM. 34

10 One axis of 6-fold symmetry. 4 3 = 7

4

TRIGONAL SYSTEM. 3 4 = 7

3 One axis of 3-fold symmetry, and one only. 4 2 = 6

1 = 1

21

3

Selection of Axes of Reference (Crystallographic Axes) in the Seven Systems.

1

The crystallographic axes (p. 35) are clearly open to arbitrary selection, and it would be possible to describe the forms of all the systems by reference to three axes perpendicular to each other. In each mineral species, however, as already stated, three planes may be used to determine the position of the axes. A characteristic double pyramid (bipyramid) may then be conceived as a fundamental form, and the axes of reference pass through the opposite solid angles of this form.

The three intercepts *a*, *b*, and *c* (p. 35), which are cut off by the planes of the selected pyramid, and which furnish the axial ratio for each particular species, are dealt with by convention in a definite order. In all but the trigonal system as treated by Miller, one axis is set upright, and the unit intercept on this is styled *c*. In regard to this axis, the other two are styled *lateral axes;* one of them is set right and left, and the corresponding unit intercept is *b*. The third then points more or less towards the observer, and the unit intercept on this is *a*. This method of setting up a crystal for description may be remembered by the fact that the first intercept considered, *a*, is on the axis that approaches the observer most directly; the next, *b*, is on the other lateral axis; the last is on the vertical axis.

To avoid additional terms, we may speak, then, of the *a*-axis, the *b*-axis, and the *c*-axis, these axes being of infinite length; $a : b : c$ expresses the ratio of the three lengths determined on these axes by the inclination of the planes of the naturally occurring pyramid that we have selected in any species as our unit form. When we say that, in crystals of a certain system, the three axes are unequal in length, we mean that no form within that system provides two equal intercepts on our established group of axes. When we say that in some other system two axes are always equal, it is similarly a short way of stating that our unit pyramid, the planes of which cut both these axes, is a figure in which the intercepts on these axes are equal. This, however, is not the same thing as saying that the planes of other forms that cut these axes are necessarily equally inclined to the two axes. The tetragonal system will at once provide examples of what is meant (Fig. 22).

As a very general rule, similar planes occur at both ends of a crystallographic axis. Where this is not the case, as in some crystals of low symmetry, the crystal is said to show *hemimorphism*, or to be *hemimorphic*, in respect of this particular axis (Figs. 19 and 42).

The crystallographic axes in the several systems are related to one another as follows:—

Triclinic System.—The axes, determined from three fundamental planes and a selected pyramid plane, are unequal in length, and no two are perpendicular to one another. One is set upright. Tbe longer of the two laterals is, by convention, chosen as the *b*-axis, and the crystal is held for description so that this slopes down to the right of the observer, while the *a*-axis slopes down towards him. The *a*-axis is styled the *brachy-axis* and the *b*-axis the *macro-axis*.

Monoclinic System.—The axis of symmetry is selected as the *b*-axis. The plane of symmetry which so generally occurs is set upright, and some convenient line in it, such as a zone-axis, is chosen as the vertical axis. The *a*-axis is determined by the unit bipyramid, or by a plane selected as the basal plane, that is, a plane parallel to the two lateral axes. The *a*-axis lies, like the vertical one, in the plane of symmetry, but is never perpendicular to the vertical axis. It is therefore described as the *clino-axis*, while the *b*-axis, which is always perpendicular to the *a* and *c* axes (since it is perpendicular to the plane containing them), is styled the *ortho-axis*. The clino-axis may be longer or shorter than the ortho-axis, and no two axes are equal in length.

Rhombic System.—Whether two or three planes of symmetry are present, the intersection of two of them is conveniently selected as the vertical axis. The *a* and *b* axes are both perpendicular to the *c*-axis and to one another. The longer of them or *macro-axis* is set right and left. The shorter or *brachy-axis* then points directly at the observer. The three axes are all unequal in length. Where, as occurs in almost all cases in this system, three planes of symmetry are present, their intersections conveniently indicate the three axes; but no custom has prevailed as to which of these three unequal axes should be set upright.

Tetragonal System.—The axis of 4-fold symmetry, or one of the axes of 2-fold symmetry when this is absent, is set vertical. There are in all cases two directions in the ideal crystal perpendicular to this axis and equal in length. These are used as the *a* and *b* axes. In crystals of the highest class of symmetry in this system, there are four axes of 2-fold symmetry perpendicular to the vertical axis and 45° apart. The alternate ones are thus perpendicular to one another, and either of the two pairs furnishes two lines of equal length which may be used as the *a* and *b* axes.

CUBIC SYSTEM.—The three axes of symmetry that are equal and perpendicular to one another naturally provide the three crystallographic axes, and it is immaterial which position is assigned to each.

HEXAGONAL SYSTEM.—The peculiar symmetry of this system suggested to Bravais the use of a vertical crystallographic axis, that of 6-fold symmetry, and of *three* lateral axes perpendicular to it and 60° apart. Since these lateral axes are equivalent in all respects, the intercepts on them are designated a_1, a_2, and a_3. If one of the three is set due right and left, a_2 is measured on this axis, a_1 on the axis pointing somewhat to the left of the observer, and a_3 on that which points somewhat to his right. The order of numbering is easily remembered, since in most drawings of crystals in any system the *a*-axis is directed somewhat to the left. a_1 corresponds in the hexagonal system with this axis; the next axis considered is that which corresponds with the *b*-axis in previous systems; the intercept on the extra or intercalated axis is then naturally a_3. The unit intercept on the vertical axis is styled *c* as usual.

TRIGONAL SYSTEM.—This system was so long regarded as a derivative from the hexagonal, by the suppression of half the number of possible faces in certain forms, that the hexagonal system of axes has been adopted for it also, the axis of 3-fold symmetry being set vertical. Miller, on the other hand, set this axis of symmetry upright, but did not regard it as a crystallographic axis. He grouped round it three crystallographic axes equally inclined to it and to one another, the angles of inclination never being right angles. These three axes thus resemble the crossing supports of a gypsy kettle. Their inclination in each species is determined by the three edges of some possible three-sided pyramid in that species, the axes being made parallel to these edges. Miller utilised this grouping of axes also in the description of hexagonal forms. While Miller's method remains generally established, on grounds of crystal-structure, for trigonal forms, it presents a difficulty in the abolition of the vertical crystallographic axis; moreover, the notation of the individual crystal-faces, while simpler than on the Bravais plan, gives symbols absolutely different from those of all the other systems.

Hence, in an introductory work, where mineralogy may be regarded as a step towards other subjects, the Bravais system of axes may be retained for the trigonal as well as for the hexagonal series of forms.

Classification of Planes by reference to the Axes.

A single crystal-plane has been styled a *pedion*.

A pair of parallel planes is styled a *pinacoid*, a word simply meaning "like a slab."

Where one vertical and two lateral axes are employed:—

(i) A plane may cut all the three crystallographic axes, and is styled a *pyramid* plane, because a group of such planes, similar and cutting the vertical axis at the same distance from the centre of the crystal, forms a typical pyramid.

(ii) A plane may cut one lateral axis and the vertical axis, being parallel to the other lateral axis. Two such planes would form a gable-roof, such as the Greeks styled *doma*. Such planes are called therefore *dome* planes. The two possible groups of such planes are named after the lateral axis to which the planes are parallel. In the monoclinic system we thus have clinodomes and orthodomes. In the triclinic and rhombic systems we have brachydomes and macrodomes. Since these dome-forms are in reality prisms lying more or less horizontally, they are often called clinoprisms, orthoprisms, macroprisms, and brachyprisms.

(iii) A plane may cut the two lateral axes only, being parallel to the vertical axis. It is called a *prism* plane.

(iv) A plane may cut one axis only, being parallel to the other two. A pair of such planes, at opposite ends of the axis which they cut, forms a particular type of pinacoid. It is convenient to call these *principal pinacoids*, three kinds being possible when we describe a crystal with reference to a system of three axes. On the same system of nomenclature that is applied to dome-planes, we have in the monoclinic system clinopinacoids and orthopinacoids, the planes of which are parallel to the vertical axis and to the clino-axis and ortho-axis respectively, and in the triclinic and rhombic systems brachypinacoids and macropinacoids. The pinacoid the planes of which are parallel to the two lateral axes is the basal pinacoid, composed of two *basal planes*.

In crystals where high symmetry prevails, the occurrence of one group of planes may necessitate the occurrence of some other group. Thus in certain classes of the tetragonal system the four planes of one dome are accompanied by the four of the other, and a special type of bipyramid results. In the cubic system, the three principal pinacoids always occur together, forming a cube. In these cases, special names are given to the forms produced. In the cubic system, planes that are strictly pyramid planes, according to our definition, may be so inclined as to give unequal intercepts on two or even three of the axes. The highly symmetrical structure of the crystals then causes the development of a number of such planes on their surfaces, far in excess of the eight that would give rise to a bipyramid. The resulting forms receive, in consequence, distinctive names.

The Fundamental Law of Crystallography.

The relations of crystal-forms within the same mineral species, or class of symmetry, or crystallographic system, are difficult to follow from mere description. Considerable experimental help may be gained from employing a system of axes and a glass plate of suitable size to lay against them. Three knitting-needles thrust through a small ball of worsted, which holds them together in the centre, make a good model of an axial system. The needles can be kept perpendicular to one another, or can be pressed aside at various angles, as required. The glass plate can be laid against them without hiding the intercepts cut off by it.

With such a model, the glass plate may be used as a pyramid-plane, cutting all three axes at different distances from the centre. For the general case, these three intercepts may be chosen without any thought of their relation to one another, so long as they are unequal. These are the conditions in the triclinic, monoclinic, and rhombic systems. The glass plate, when so placed, may be regarded as a plane of the unit pyramid in some particular species, giving us the axial ratio $a : b\ (= 1) : c$ for that species. If we now shift it, so that the ratio between two of the intercepts remains the same, but so that it cuts the third axis at a relatively longer or shorter distance than before, we have produced another kind of pyramid plane.

It by no means follows, however, that this pyramid plane is one that nature finds possible in crystals of the mineral species that furnished the axial ratio of the first plane. The grouping of the molecules and atoms within crystals excludes a large number of geometrical forms, and connects the possible variations in the same species by a law known as the LAW OF RATIONAL INTERCEPTS. The discovery of this law is due to Haüy (p. 31), and all modern reasoning as to crystal-structure is based upon it.

The law may be thus stated. If the intercept made on any axis by a plane inclined to that axis is regarded as unity $(= 1)$, the intercepts made on the same axis by any other planes in crystals of the same mineral species are either infinite, in which case the plane is parallel to the axis, or can be expressed by small whole numbers or by simple fractions.

That is to say, when a unit form has been selected, and the unit ratio $a : b : c$ has been determined from it, any numbers representing the intercepts in other forms of the same mineral species will be commensurable with those which they respectively replace in the unit axial ratio.

To take a simple case, a variation from the height of the selected pyramid in a mineral species may produce a pyramid of just half the height, or three times the height, and so forth, in proportion to the lateral dimensions, but not one in which the relationship to the intercept *c* would need to be represented by a surd. Variations may take place along all the three axes, so that there is a complete departure from the original axial ratio accepted as that of the unit form; but the figures representing the lengths of this second series of intercepts will always obey the law of rationality in regard to those of the unit form.

This not only limits the possible forms in a given series, but it excludes certain types of geometrical symmetry. The possible variations, moreover, rarely give us an intercept which is more than seven times as long in relation to the others as was the corresponding intercept in the unit form. Or, if we regard the unit intercept as the longest, the variations from it are rarely smaller than one-seventh.

Notation of Crystal Faces.

For the description of crystals, it is desirable to have a shorthand notation by which any possible face can be indicated. If such a notation, moreover, expresses the ratio of the intercepts cut off by a plane in terms of those of the unit form, it is clearly much more than a shorthand statement, and may even serve in calculations. Such a notation supplies an exact description of the plane, provided that we know the inclinations of the axes and the axial ratio in the form selected as the unit.

The survivor of several systems of notation is that due to W. Whewell (1825) and W. H. Miller (1839), early in the nineteenth century, which has now received a world-wide adoption. The only important changes that have been made since 1839 are in the order in which the axes are considered and in the number of axes employed in the hexagonal, and sometimes in the trigonal, system.

In order that every face may receive a separate notation, it is necessary to attribute different signs to the two ends of the same axis. In a 3-axial system, where one axis is vertical, the positive sign is given to the three ends that may be regarded, by common custom, as the most important, namely, the front, right-hand, and top ends (Fig. 10). The other ends receive a negative sign. In the Bravais scheme for the hexagonal and trigonal systems, the signs on the lateral axes are arranged alternately (Fig. 11), beginning with the front end of the a_1-axis as positive. Here, then, on the a_3-axis, we have a positive sign on the side farthest from the observer. In Miller's three-axial scheme for these systems, the upper ends of the three axes are positive and the lower ends are negative.

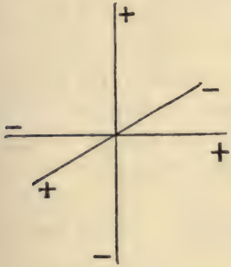

FIG. 10.

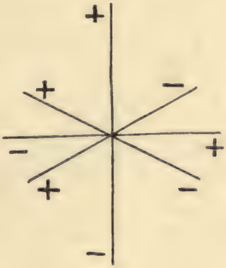

FIG. 11.

In considering the principles of Miller's notation, we start with the unit pyramid-plane, cutting the three axes X, Y, and Z respectively at the distances *a*, *b*, and *c*, and this plane furnishes the axial ratio (Fig. 8). The three unit distances, the parameters, may be each designated by 1, provided that we realise that these three units may have very different numerical values when expressed as actual lengths.

All variations from the unit plane may then be regarded as taking place in the space between that plane and the point in which the axes intersect. Thus in Fig. 12, where ABC is the unit pyramid-plane, another pyramid may occur, governed by the law of rationality, of one-half the vertical height. If the intercepts of ABC are expressed as 111, those of the plane ABD are $1 1 \frac{1}{2}$. Another plane, EBD, has an intercept on X which is only one-third of *a*; its three intercepts are $\frac{1}{3}1\frac{1}{2}$. We must keep in mind that the value $\frac{1}{3}$ is really $\frac{a}{3}$; the second value is $\frac{b}{1}$; the third is $\frac{c}{2}$. Miller simplified this possible notation by conceiving the three values in such a case as written $\frac{111}{312}$, and by using as *indices* only the denominators. The resulting *symbol* for the face EBD is made up of the three *indices* 312.

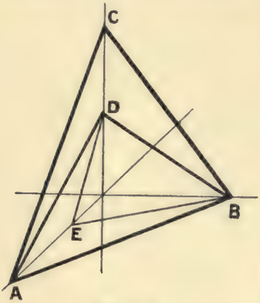

FIG. 12.

Miller's indices are, in fact, the denominators of fractions the numerators of which are all 1. Through the operation of the law of rational intercepts, they are always themselves rational. They are always whole numbers, rarely exceeding 7.

If the intercepts are, as is quite possible, $\frac{1}{2}a$, $\frac{4}{5}b$, $\frac{2}{3}c$, these can be equally written $\frac{444}{856}$, or $\frac{111}{856}$, since the planes here expressed in the two series of fractions are parallel with one another and on the same sides of the axes, and are therefore crystallographically identical. The notation is thus reduced to three fractions the numerators of which are 1; Miller's symbol is consequently 856.

Rarely, the indices work out as double figures, such as 5.14.18, which occurs in a crystal of the rhombic mineral Brookite. In such cases, a stop shows the limits of each index. When a plane is parallel to an axis, the index 0, the reciprocal of infinity, appears in the symbol. 001 thus indicates a basal plane.

In writing the notation of a crystal, the symbols of the planes are enclosed in simple brackets, as (321). More elaborate brackets are used when we wish to express a whole form by the symbol of one of its planes. {111} may thus indicate the eight planes of a unit bipyramid.

The positive and negative signs at the ends of the axes enable every face of the same form to receive a distinct symbol; but the negative sign is alone written, an intercept made at the negative end of an axis being represented by its index with a minus sign over it. The eight planes of the unit bipyramid are thus as follows (Fig. 9):—

(111) the front right hand top plane.
$(1\bar{1}1)$,, front left ,, ,, ,,
$(\bar{1}11)$,, back right ,, ,, ,,
$(\bar{1}\bar{1}1)$,, back left ,, ,, ,,
$(11\bar{1})$,, front right hand bottom plane.
$(1\bar{1}\bar{1})$,, front left ,, ,, ,,
$(\bar{1}1\bar{1})$,, back right ,, ,, ,,
$(\bar{1}\bar{1}\bar{1})$,, back left ,, ,, ,,

It will be noticed that the members of each pair of parallel planes have opposite signs to their indices. The symbols will always be the same for such planes, but with this reversal of sign. The planes $(2\bar{3}1)$ and $(\bar{2}3\bar{1})$ are thus shown by their symbols to be parallel.

It is excellent practice to write the symbols in pencil on each face of wooden or cardboard models of various crystals. In the *triclinic*, *monoclinic*, and *rhombic* systems, we must remember that the three unit indices represent three different lengths of intercept, usually incommensurable with one another, the axial ratio being expressed as nearly as possible to four or five places of decimals. (123) does not mean a plane one of whose intercepts is one-half and another one-third the length of the first. In the *tetragonal* system, however, the two first units in (111) express intercepts that are actually equal, while the third unit represents some longer or shorter intercept, usually incommensurable with them. Here the axial ratio, where $a = b$, requires only the statement of $a : c$, and a is stated as 1. In the tetragonal system, therefore, the symbol (121) expresses a plane that cuts the a-axis at the unit distance and the b-axis at half that distance; but in (122) the second 2 expresses merely half the unit distance on the c-axis, and has no equality with the 2 which precedes it in the symbol. The intercepts on the a and b axes in this system, however, can never be irrational. Similarly, in the 4-axial symbols for the *hexagonal* and *trigonal* systems, the first three indices express intercepts that are rational with regard to one another, the fourth intercept, that on the *c*-axis, being usually incommensurable. Here again $a : c$ provides the axial ratio, a being stated as 1. Through the use of the minus sign for one or two of the first three indices in these systems, it will be observed that the sum of these three indices always = 0.

In the *cubic* system, *and in this system only*, (111) expresses a plane with three equal intercepts, while (123) represents a plane that cuts the *a*-axis at unit distance, the *b*-axis at one-half of that same distance, and the *c*-axis at one-third of that same distance.

It often happens that a general symbol is required for planes cutting two or more axes. The letters $h\ k\ l$ are then employed. The lengths of the intercepts represented by these letters are respectively $\frac{a}{h}, \frac{b}{k}, \frac{c}{l}$. (hkl) thus represents any plane cutting the three axes at their positive ends and forming three different intercepts. (hhl) stands for a plane cutting two similar lateral axes at their positive ends and at the same distance from the centre. (okl) is a right-hand top dome-plane. The Bravais scheme for the hexagonal and trigonal systems introduces the fourth index-letter i. Here, as will be seen later, one at least of the letters hik must be surmounted by the negative sign. The same symbols placed in the more elaborate brackets indicate forms in general. {hkl} employed for a form in the most symmetrical class of the rhombic system thus represents any possible bipyramid.

The Representation of Crystals.

Drawings of crystals are usually made with the eye looking a little down on the plane containing the two lateral axes, and with the *a*-axis sloping a little to the left of the observer. The *b*-axis thus does not lie in the plane of the paper, except by chance in the case of some triclinic crystal. The *c*-axis, however, is always upright. The projection employed is styled CLINOGRAPHIC, and the eye is supposed to regard the crystal from an infinite distance. Perspective effects are thus eliminated, all equal vertical lines remaining equal in the drawing. Although other lines are reduced by foreshortening, these that are parallel in the crystal remain parallel in the drawing.[1]

The representation of crystals by STEREOGRAPHIC PROJECTION is employed by crystallographers to display the symmetral features and the precise relations of the faces of a form. If we imagine the crystal to be set with one of its axes upright and to be surrounded symmetrically by a sphere, lines may be drawn from the centre of the crystal, and therefore of the sphere, perpendicular to each of the planes the intersections of which give rise to the crystal-faces. These lines, when produced, cut the sphere at certain points, which are called the *poles* of the faces. Each face may then be represented by a single point, its pole. A zone of upright planes will yield a series of poles along the equator of the sphere. The poles of any zone of faces lie on a great circle of the sphere. The pole of a face parallel to the equatorial plane of the sphere coincides with the north or south pole of the sphere. The poles of two parallel faces lie at opposite ends of a diameter of the sphere. The angle made at the centre of the sphere by the lines perpendicular to any two faces is the supplement of the actual interfacial angle, that is, it is the angle usually given by the reflective goniometer. The crystal may thus be represented on a sphere by a process known as *spherical projection.*

The sphere, thus conceived to surround the crystal, is *stereographically* projected on to its equatorial plane in the following manner. For the upper hemisphere, lines are supposed to be drawn from each face-pole to the lower pole of the sphere. The points where these lines cut the equatorial plane represent in the projection the poles upon the sphere, and are indicated by a dot upon the plane of projection. Similarly, the poles of the planes projected on the lower hemisphere of the spherical projection are represented by the points where lines joining them with the upper pole of the sphere intersect the plane of stereographic projection. These points are marked by a small ring.

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[1] See especially M. Reeks, "Hints on Crystal Drawing" (1908), and A. E. Tutton, "Crystallography" (1911), p. 382.

When the plane of projection is a plane of symmetry of the crystal, there will be in every case a pole of the lower series corresponding on the plane of projection with one belonging to the upper series. In that case a spot surrounded by a ring is drawn.

The poles of faces belonging to the same zone lie, as already remarked, on great circles in the spherical projection of the crystal, that is, on circles whose planes pass through the centre of the sphere. Such circles appear in the stereographic projection as straight lines when they pass through the poles of the sphere; or as arcs of circles when they are oblique to the equatorial plane; or as a circle, bounding the stereographic projection, in the case of the vertical zone. When straight lines thus arise, they are diameters of the circle of projection; when arcs arise, the line joining their terminations on the circle of projection is a diameter of that circle; when a circle arises, it coincides, as already indicated, with the circle of projection.

The ends of axes of symmetry may be stereographically projected, and signs may be added to show their nature. An ellipse represents 2-fold symmetry; a triangle, 3-fold; a square, 4-fold; and a hexagon, 6-fold symmetry (Fig. 13).

FIG. 13.

In projections of triclinic crystals, the *c*-axis does not coincide with the vertical axis of the sphere, since the plane of projection is chosen as parallel with the basal plane, and includes the two lateral axes. In the monoclinic system, the plane of projection contains the *a* and *c* axes, and the *b*-axis coincides with the vertical axis of the sphere. In the other systems the *c*-axis is perpendicular to the plane of the lateral axes; since this plane coincides with the plane of projection, the *c*-axis coincides with the vertical axis of the sphere.

A typical example of the projection of a rhombic crystal, taken from Bauerman's "Systematic Mineralogy," is shown in Fig. 14.

The representation of crystals by MODELS has been referred to on p. 36. It is very desirable, and indeed imperative, to have a set of such models at hand when studying the elements of crystallography. The makers of wooden models usually employ ratios for the intercepts that occur in well known minerals, and the combinations are constructed from actual crystals. In estimating the relations of the planes represented to the axes, two glass slips should be employed, such as are

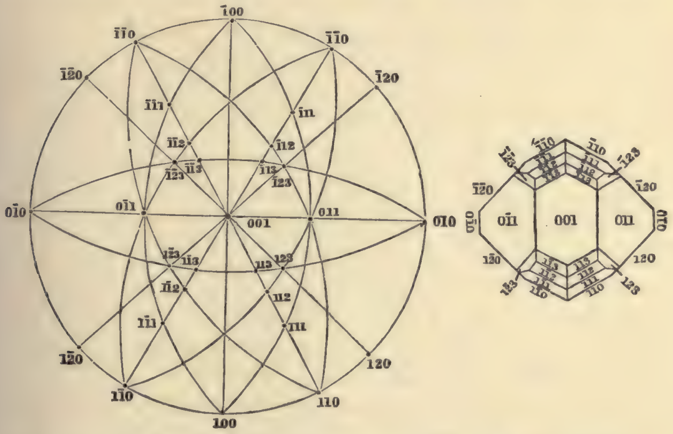


FIG. 14.—Stereographic projection of a crystal of topaz. The crystal, viewed down the *c*-axis, is shown upon the right.

used for mounting microscopic objects. These can be applied to the faces without hiding the model, and the two slips can be moved until they meet, when it is desired to observe the angle between any two planes that are not in contact in the model.

CHAPTER IV

CLASSES OF SYMMETRY AND TYPICAL FORMS IN THE SEVEN CRYSTALLOGRAPHIC SYSTEMS

THE thirty-two classes of symmetry (p. 38) that are possible under the limiting conditions imposed by the law of rational indices are grouped under seven systems. Some of these classes are represented far more frequently than others in rock-forming minerals or in common ores, and thus assume importance from the point of view of natural history. In each system, the class that displays the highest possible symmetry illustrates most suggestively the nature of the system; in general, moreover, it is the class most favoured by mineral species which crystallise in that system. The classes will, then, be treated within each system, so far as is convenient, in order of decreasing symmetry. On the other hand, there are great educational advantages in dealing with the 3-axial systems in the order of increasing symmetry, the variety of forms possible in the triclinic system being far fewer than those in the cubic system. The trigonal and hexagonal systems will be taken at the close.

The essential features of each system, and the arrangement of the crystallographic axes, have been stated on pp. 38–43. The numbers in brackets following the heading of each symmetral class are those of the class in the whole series of thirty-two, and will facilitate comparison with the descriptions in larger treatises.

Triclinic System.

Though few minerals crystallise in this system, it possesses geological importance through the rock-forming group of the felspars.

Class I (2).—No planes or axes of symmetry; but each plane is accompanied by one parallel with it on the opposite side of the centre of the crystal ("symmetry about a centre").

Quarter-bipyramids.—Any pair of parallel planes of a bipyramid constitutes a possible and independent form, the four forms thus consisting of $(hkl)(\bar{h}\bar{k}\bar{l})$; $(h\bar{k}l)(\bar{h}k\bar{l})$; $(\bar{h}kl)(h\bar{k}\bar{l})$; $(\bar{h}\bar{k}l)(hk\bar{l})$. Hence a single pyramid plane may appear in the upper half of a triclinic crystal of Class I, balanced merely by a parallel one in the lower half.

Half-macrodomes (*hemimacrodomes*).—The pairs of planes $(h0l)(\bar{h}0\bar{l})$ and $(\bar{h}0l)(h0\bar{l})$ may occur independently.

Half-brachydomes (*hemibrachydomes*).—Similarly the pairs $(0kl)\ (0\bar{k}\bar{l})$ and $(0\bar{k}l)\ (0k\bar{l})$ may be independently developed.

Half-prisms (*hemiprisms*).—The vertical pairs of planes $(hk0)\ (\bar{h}\bar{k}0)$ and $(h\bar{k}0)\ (\bar{h}k0)$ may occur independently.

Macropinacoid pair.—$\{100\}$, including $(100)(\bar{1}00)$.

Brachypinacoid pair.—$\{010\}$, including $(010)(0\bar{1}0)$.

Basal pinacoid pair.—$\{001\}$, including $(001)(00\bar{1})$.

Example (Fig. 15).—A crystal of a triclinic felspar, consisting of the unit quarter bipyramid $\{11\bar{1}\}$; the unit half macrodome $\{10\bar{1}\}$; the complete unit prism $\{110\}$; the brachypinacoid $\{010\}$; and the basal pinacoid $\{001\}$.

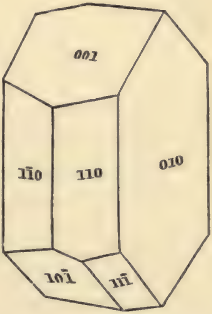


Fig. 15.—Crystal of triclinic felspar.

Class II (1).—The forms in this class consist of single planes. One-eighth of a bipyramid, one-quarter of a dome or of a prism, or a single basal plane, may thus occur. There is not even symmetry about a centre.

Monoclinic System.

A large number of rock-forming minerals crystallise in this system, including orthoclase, augite, and hornblende.

Class I (5).—One plane of symmetry, which is set vertical, and an axis of 2-fold symmetry perpendicular to it. It will be remembered that the *a* and *c* axes are selected in the plane of symmetry, and are never at right angles to one another, while the axis of symmetry is utilised as the *b*-axis.

Hemibipyramids.—The symmetry is satisfied if the two front top planes and the two back bottom planes of a bipyramid are developed, or the two back top planes and the two front bottom ones. These two half bipyramids may be symbolised as $\{hkl\}$ and $\{\bar{h}kl\}$. The former, the planes of which face the obtuse angle made by the *c* and *a* axes, has unfortunately been styled negative, and the latter positive. Each hemibipyramid forms in reality an inclined prism, and they have been styled "fourth-order prisms."

Hemiorthodomes.—Either (hol) $(\bar{h}o\bar{l})$ or $(\bar{h}ol)$ $(ho\bar{l})$ satisfy the symmetry.

Clinodome.—Here all four planes are required, owing to the existence of both the plane and the axis of symmetry. The generalised form is $\{okl\}$.

Prism.—$\{hko\}$, representing all four planes. The cross-section will always yield a rhombus, not a mere parallelogram as in the triclinic system.

Orthopinacoid pair. $\{100\}$.
Clinopinacoid pair. $\{010\}$.
Basal pinacoid pair. $\{001\}$.

EXAMPLE (Fig. 16).—A crystal of borax, consisting of the hemibipyramids $\{\bar{1}11\}$ and $\{\bar{2}21\}$; the prism $\{110\}$; the orthopinacoid pair $\{100\}$; the clinopinacoid pair $\{010\}$; and the basal pinacoid pair $\{001\}$.

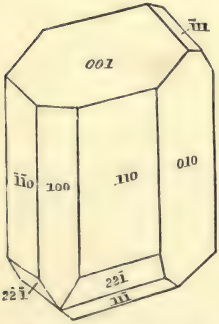


FIG. 16.—Crystal of borax.

CLASS II (3).—One plane of symmetry, but no axis of symmetry. The crystals are hemimorphic on both the vertical axis and the clino-axis; thus we may find the upper or lower half of a clinodome, or a single basal plane, or the front or back pair only of the vertical prism. Both clinopinacoid-planes occur together, but one plane of the orthopinacoid by itself satisfies the symmetry.

CLASS III (4).—One axis of 2-fold symmetry, but no plane of symmetry. Hemimorphic forms result on the *b*-axis, the ends of which need not be terminated by similar planes. The right-hand or left-hand half of a clinodome or of a prism may thus occur independently, producing wedge-like forms known as *sphenoids.* The bipyramid may here be represented by a front right-hand top plane (hkl) and a back right-hand bottom plane $(\bar{h}k\bar{l})$ only, and so forth.

Rhombic System.

A number of minerals of geological importance crystallise in this system, including certain pyroxenes, barytes, aragonite, and sulphur.

CLASS I (8).—Three planes of symmetry perpendicular to one another, intersecting in three axes of 2-fold symmetry, which are chosen as the crystallographic axes.

Bipyramid {hkl}.—All eight planes must be present. They are scalene triangles.

Macrodome {hol}.—All four planes (Fig. 17).

Brachydome {okl}.—All four planes (Fig. 17).

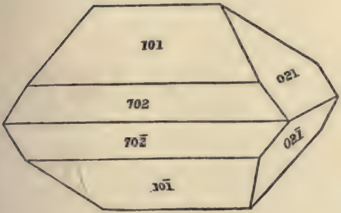


FIG. 17.—Rhombic crystal consisting of two macrodomes and one brachydome.

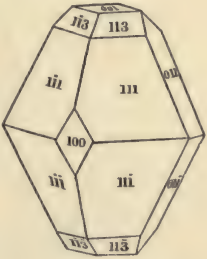


FIG. 18.—Crystal of sulphur.

Prism {hko}.—All four planes.
Macropinacoid pair. {100}.
Brachypinacoid pair. {010}.
Basal pinacoid pair. {001}.

EXAMPLE (Fig. 18).—A crystal of sulphur, consisting of the unit bipyramid {111}; a bipyramid {113}; the unit brachydome {011}; the macropinacoid pair {100}; and the basal pinacoid pair {001}.

Class II (7).—Two planes of symmetry perpendicular to one another, intersecting in an axis of 2-fold symmetry, which is utilised as the *c*-axis. The crystals are thus hemimorphic on the vertical axis.

Pyramids, upper and lower, $\{hkl\}$ and $\{hk\bar{l}\}$, and not bipyramids, occur.

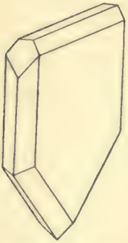


Fig. 19.—Crystal of hemimorphite (after Dana).

The prism and vertical pinacoid pairs occur, as in Class I; but the upper or lower basal plane may occur alone.

Example (Fig. 19).—A crystal of hemimorphite, consisting of the pyramid $\{12\bar{1}\}$; the top macrodome pair {301}; the top brachydome pair {031}; the unit prism {110}; the brachypinacoid pair {010}; and the basal plane {001}. It will be noted, by the style of bracket used, that this plane constitutes a complete crystal form.

Class III (6).—No plane of symmetry, but three axes of 2-fold symmetry perpendicular to one another.

Bisphenoid (Fig. 20) $\{hkl\}$ or $\{h\bar{k}l\}$.—A bisphenoid takes its name from its being formed of two wedges (Fig. 20). For every set of indices represented by *hkl*, there are two distinct bisphenoids, one of which is, as it were, the reflection of the other; they are not, however, convertible into one another by rotation. They form, therefore, an "enantiomorphous" pair; the one containing the face with all its indices positive is known as the "right-handed" form, $\{h\bar{k}l\}$ being the "left-handed." The planes are scalene triangles, and the horizontal edges of the two wedges formed by them are not perpendicular to one

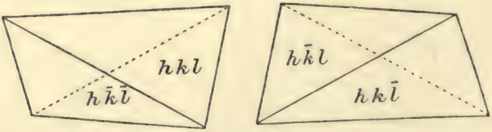


Fig. 20.—Right-handed and left-handed rhombic bisphenoids.

another. The crystallographic axes emerge in the centres of opposite pairs of edges, being, in fact, the axes of 2-fold symmetry.

The other forms in this class do not differ from those in Class I. If one plane of the macrodome, for instance, occurs, all four planes are required, by the fact that three perpendicular axes of symmetry have to be satisfied. Similarly with the prism, which may here be regarded as a bisphenoid, the vertical axis of which is infinitely long. The pinacoid pairs, it may be noted, each truncate in combinations two edges of the bisphenoid. That is to say, if the bisphenoid is set up with one pair of edges horizontal, the four other edges lie in four vertical planes which make a rectangular prism round about the crystal.

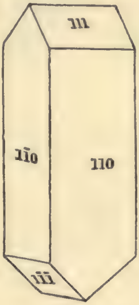


FIG. 21.—Crystal of epsomite.

EXAMPLE (Fig. 21).—Epsomite exhibits combinations of a right-handed unit bisphenoid {111} with a unit prism {110}.

Tetragonal System.

No important rock-forming mineral crystallises in this system.

CLASS I (15).—Four planes of symmetry making angles of 45° with one another, and intersecting in an axis of 4-fold symmetry, which is selected as the *c*-axis. Also a fifth plane of symmetry perpendicular to these, the four consequent intersections being axes of 2-fold symmetry. These horizontal axes of symmetry form two pairs perpendicular to one another, the members of a pair being equal in length Either pair is taken to provide the *a* and *b* axes. In this system, then, we encounter two crystallographic axes of equal length.

Ditetragonal Bipyramid {hkl}.—This form is composed of sixteen similar scalene triangles, eight above and eight below, the planes forming different intercepts on the *a* and the *b* axes. These two intercepts are not, however, incommensurable, since the lateral axes are equivalent to one another in all respects. Hence the geometrical form with a regular octagon as its plan and isosceles triangles as its faces is excluded in nature. In crystals, only the alternate angles of the octagonal plan are equal to one another (Fig. 22). A ditetragonal bipyramid commonly occurring in zircon is {311}, in which each pyramid-plane forms an intercept on one lateral axis which is one-third of that formed upon the other. Ditetragonal forms are so far only known in nature in combinations.

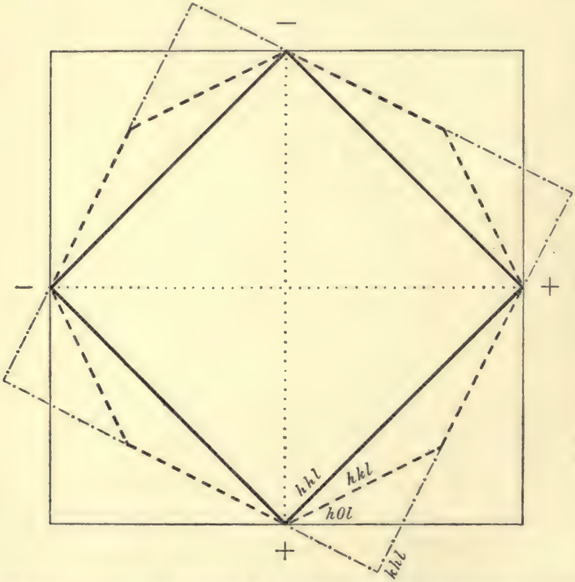


FIG. 22.—Horizontal sections of forms of the tetragonal system. The lines of round dots represent the lateral axes.

Tetragonal Bipyramid of the First Order (Fig. 22) {hhl}.—This is the ordinary bipyramid, here formed of eight planes that are isosceles triangles. In the unit form {111}, the first two indices represent equal lengths.

Tetragonal Bipyramid of the Second Order (Fig. 22) {hol}.—This, as explained on p. 44, may be regarded as a combination of the complete domes, the occurrence of one necessitating the occurrence of the other. The plan being square, and the intercept on the *c*-axis being the same for both domes, a tetragonal bipyramid arises which is only distinguishable in combinations. Where the two types of bipyramid occur together, the selection of one as first order places the planes of the other in the second order relation to the axes.

Seeing that in any bipyramid or pyramid the index *l* may = 0, each of the foregoing bipyramids has a corresponding prism, thus :—

Ditetragonal Prism {hk0}.

Tetragonal Prism of the First Order {hh0}, written as {110}

Tetragonal Prism of the Second Order {100}.—This prism obviously represents the two vertical principal pinacoids, which must occur in this class in combination, forming a square prism.

Basal pinacoid pair {001}.—This is the only pair of planes that can satisfy the exacting symmetry of this class.

EXAMPLE (Fig. 23).—A crystal of zircon, showing a second order prism combined with the first order bipyramid {111} and the ditetragonal bipyramid {311}.

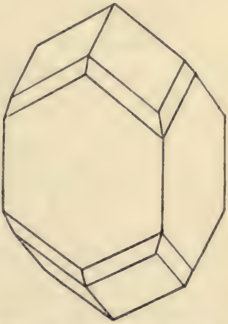


FIG. 23.—Crystal of zircon (after Tutton).

CLASS II (13).—Four planes of symmetry making angles of 45° with one another, and intersecting in an axis of 4-fold symmetry, which is chosen as the *c*-axis. Two alternate intersections of the vertical planes of symmetry with the horizontal plane are taken as the *a* and *b* axes, as in Class I. ; but this plane is not a plane of symmetry, nor are there any horizontal axes of symmetry. The crystals are thus hemimorphic on the *c*-axis.

Three *pyramids*, *Ditetragonal*, *Tetragonal first order*, and *Tetragonal second order*, and the single *Basal plane* {001} or {00$\bar{1}$} are the characteristic forms. The prisms are the same as in Class I.

CLASS III (12).—One axis of 4-fold symmetry and a plane of symmetry perpendicular to it are the only elements of symmetry.

Third-order Tetragonal Bipyramids.—{hkl} and {khl}, convertible into one another by rotation (Fig. 22 includes {khl}).

Third-order Tetragonal Prisms.—{hko} and {kho}, similarly convertible (Fig. 24).

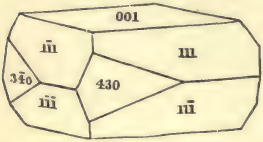


FIG. 24. — Tetragonal crystal showing right-handed third order prism, {430}.

In each of the above pairs of forms, that which makes the longer lateral intercept, represented by the lesser index *k*, on the *b*-axis is styled right-handed, and the other form is left-handed. The two forms are indistinguishable on rotation about the vertical axis. They are of course only recognisable when combined with others, such as first or second order forms. As in ditetragonal forms, the intercepts on the two lateral axes must be commensurable one with another.

EXAMPLE.—Scheelite, calcium tungstate, in which a first, a second, and two third-order bipyramids occur in the same crystal, the third order forms being {131} and {313}. Compare the basal plans in Fig. 22.

CLASS IV (9).—The axis of 4-fold symmetry is alone present. Owing to the absence of the horizontal plane of symmetry, the forms are related to those of Class III as those of Class II are to those of Class I. The upper or lower halves of third order bipyramids occur therefore in this class as *third order pyramids*, recognisable as distinct from those of Class II only in combinations. Wulfenite, lead molybdate, crystallises in this class.

CLASS V (11).—All the five axes of symmetry of Class I are present, that of 4-fold symmetry being set vertical; but there are no planes of symmetry. The forms in this class with the symbol {hkl} and {khl} are distinct from those of all the other classes, whether seen in combination or not. These two forms are *Tetragonal trapezohedra*, each bounded by eight trapezoidal faces. {hkl}, the right-handed form, has an enantiomorph in {khl}, the left-handed trapezohedron.

CLASS VI (14).—Two planes of symmetry, intersectiing in an axis of 2-fold symmetry, which is set vertical and serves as the *c*-axis. In addition, two other axes of 2-fold symmetry, perpendicular to *c* and to one another, and equal in length. These bisect the angles between the two planes of symmetry, and are utilised as the crystallographic axes *a* and *b*. There is no horizontal plane of symmetry.

Tetragonal Scalenohedron (Fig. 25) $\{hkl\}$.—A form bounded by eight scalene triangles, four above alternating with four below. The *c*-axis unites the solid angles formed by the meeting of these planes above and below, while the lateral axes unite the centres of opposite pairs of lateral edges. Positive and negative forms occur; see description of the next form.

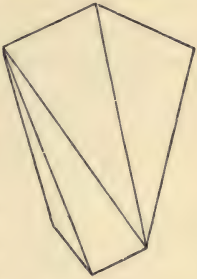


FIG. 25.

Tetragonal Bisphenoid $\{hhl\}$ or $\{h\bar{h}l\}$.—The bisphenoids are the typical forms of this class, as in the corresponding class of the rhombic system. They are each bounded by four isosceles triangles, and in this case the horizontal edges of the two wedges of which they are composed are perpendicular to one another. The axes emerge in the centres of opposite pairs of edges, the lateral ones being equal in length. By rotation, $\{hhl\}$ can be converted into $\{h\bar{h}l\}$, owing to the equality of the lateral axes, and the forms are thus not enantiomorphous, although the one is the mirror-image of the other. They are therefore distinguished merely as positive and negative, the positive one containing the face that has all its indices positive (Fig. 26). Compare Class III in the Rhombic system.

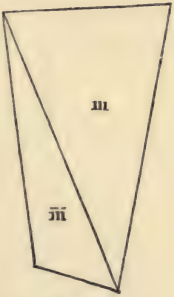


FIG. 26.

Other forms in this class resemble those of Class I; the tetragonal scalenohedron $\{hkl\}$, which represents the ditetragonal bipyramid, gives rise, by infinite extension of its vertical intercepts, to the *Ditetragonal prism*, $\{hko\}$.

EXAMPLE.—Copper pyrites, which usually crystallises in bisphenoidal forms.

CLASS VII (10).—The axes of symmetry are those of Class VI, but there are no planes of symmetry. The typical forms are four *Tetragonal bisphenoids of the third order;* $\{hkl\}$ and $\{khl\}$ are "positive" forms, and $\{h\bar{k}l\}$ and $\{k\bar{h}l\}$ are "negative." These are, of course, only distinguishable when in combination with other forms, and their occurrence marks the low symmetry of the crystal-structure.

Cubic System.

The equality of the three crystallographic axes in this system, whether they are axes of 2-fold or 4-fold symmetry, furnishes six equivalent points about which similar planes arise The forms approach more nearly towards the sphere, the solid of ideal symmetry, than those of any other system. Internally, with regard to their effect on rays of light passing through them, they may be said to have attained ideal symmetry.

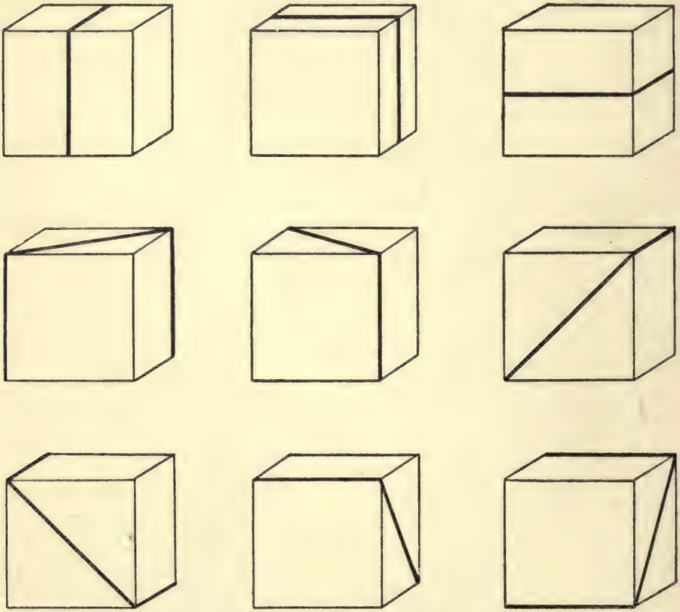


FIG. 27.—The nine planes of symmetry in Class I. of the Cubic System.

CLASS I (32).—Three axes of 4-fold symmetry, equal in length and perpendicular to one another; these unite the centres of opposite faces of a cube. Four axes of 3-fold symmetry; these unite diagonally the opposite solid angles of a cube. Six axes of 2-fold symmetry; these unite the centres of opposite edges of a cube. Three planes of symmetry perpendicular to one another and intersecting in the axes of 4-fold symmetry. Six planes of symmetry, each passing diagonally across a face and through two opposite edges of a cube; two such planes are clearly possible for each pinacoid in a cube. Hence there are nine planes of symmetry (Fig. 27), and thirteen axes of symmetry.

Hexakis-octahedron (*six-faced octahedron*) {hkl}.—This is so called because there are six faces in each eighth or octant of the form, each set of six corresponding to one plane of the bipyramid or octahedron. All the three different intercepts must here be rational with regard to one another.

The forty-eight planes necessitated by the symmetry are similar scalene triangles (Fig. 29, i.), and an umbrella, as it were, of eight such planes occurs about each end of the three axes. Where h, k, and l represent intercepts that do not differ widely, the form approximates to an octahedron, and the justice of its name is clear. Where, however, the intercepts on two axes are much longer than those on the third, the form approximates to a cube. The umbrellas of each axial termination are then more opened out. The form {321} is distinctly on octahedral lines; in {421} the umbrellas catch the eye more readily than the pyramids of six faces in each octant (Fig. 28); and in {531} the umbrellas predominate, and the form is thoroughly cuboidal.

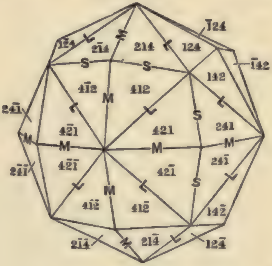
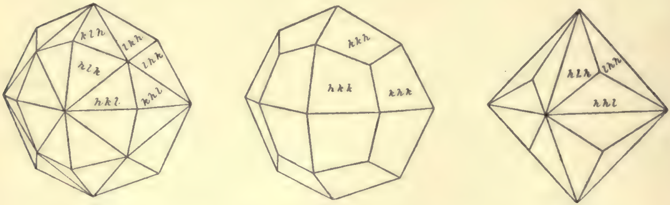


FIG. 28.

Where $h = k = l$, the form passes into {111}, the octahedron; when k and l are both 0, we have {100}, the cube. These two, then, are the *limiting forms* of the six-faced octahedron.

The six-faced octahedron occurs in combinations, as in fluor-spar, spinel, and garnet, but is rare as a separate form.

Icositetrahedron (Fig. 29, ii).—If two of the intercepts are equal and longer than that on the a-axis, the symbol becomes {hkk}, the index *h*, representing the shorter distance, being greater than *k*. Modifying the symbols for the faces in the front right-hand top octant of Fig. 29, i, accordingly, it will be seen that the upper pair of faces now becomes one face with a deltoidal form, since its constituent faces receive the same symbol and hence lie in one plane. Similarly for the other pairs of faces, and for each pair in each octant. The resulting form consists of twenty-four similar deltoids, and its limiting forms are again clearly {111}, where $k = h$, and the cube {100}, where the intercepts on two of the axes are infinite.



(i) (ii) (iii)

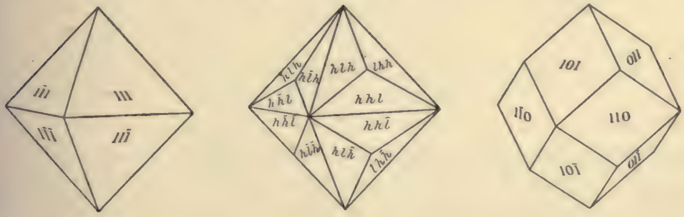
FIG. 29.—Relation between the hexakis-octahedron (i), the icositetrahedron (ii), and the triakis-octahedron (iii).

This form is well known independently in analcite, leucite, and garnet {211}.

Triakis-octahedron (*Three-faced Octahedron*) (Fig. 29, iii).—If two of the intercepts are equal, but shorter than that on the third axis, we have {hhl}, where the index h, representing the shorter distances, is greater than l. Referring again to Fig. 29, i, we see that this change in the symbol brings the two lower planes of the front right-hand top octant of {hkl} into coincidence, and similarly the planes of the left-hand and right-hand pairs above it. The resulting form has twenty-four similar sides, which are low isosceles triangles. One of its limiting forms is clearly the octahedron {111}, when $h = l$. The other is most conveniently regarded as the rhombic dodecahedron {110}, as will presently be pointed out.

Octahedron (Fig. 30, i).—This is the bipyramid of the cubic system, in which $h = k = l$, and the three unit intercepts are all equal in length. The bipyramid of the cubic system is in consequence not subject to variation in regard to any axis, the pyramid-planes (hkl), (hkk), and (hhl) requiring so many planes to be associated with them that the forms which arise cannot be treated as bipyramids. The three axes being equivalent, the angles over all the twelve edges are the same, measuring 109° 28′. Cross-sections, such as are seen in microscopic slides, commonly appear as squares or hexagons, the latter arising from an oblique cut across the crystal.

Rhombic Dodecahedron.—Referring again to the three-faced octahedron (Fig. 30, ii), when the longer distance, represented by *l*, becomes infinite, the symbol becomes {110}, and planes in adjacent octants merge into one another. In place, for example, of the two adjacent triangles (hlh) and hlh), one rhombus arises, (101). (hhl) and the plane (hh$\bar{l}$) below it merge into a vertical rhombus (110). The resulting form (Fig. 30, iii) is bounded by twelve similar rhombuses. It is as invariable as the octahedron, and the angles over all its edges measure 120°. By comparison with the forms of the rhombic system, it will be seen that we have here the prism and both kinds of domes in enforced association one with another. The rhombic dodecahedron is the form commonly assumed by garnet.

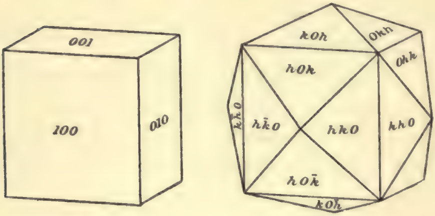


(i) (ii) (iii)

FIG. 30.—Relation between the octahedron (i), the triakis-octahedron (ii), and the rhombic dodecahedron (iii).

Tetrakis-hexahedron (*Four-faced Cube*).—We have yet to consider the variations on {hkl} where l = 0. Planes in adjacent octants now merge, pair by pair, and a figure results bounded by twenty-four rather low isosceles triangles (Fig. 31, ii). The limiting forms of {hk0} are clearly the rhombic dodecahedron, where $h = k$, and the cube, where $k = 0$. The form has usually a cuboidal aspect, as when the symbol is $\{210\}$.

Cube $\{100\}$ (Fig. 31, i).—This form is so well known that it seems pedantic to call it the *hexahedron*. It is bounded by six square faces, and all the interfacial angles are 90°. As its symbol shows, it does not include the prism of the system; but it consists of the three principal pinacoid pairs in compulsory association.



(i) (ii) (iii)

FIG. 31.—Relation between the cube (i), the tetrakis-hexahedron (ii), and the rhombic dodecahedron (iii).

The foregoing seven forms produce a great variety of combinations. The planes of the octahedron truncate the eight solid angles of the cube, and the cube-planes truncate the six solid angles of the octahedron. The planes of the rhombic dodecahedron truncate the twelve edges of the octahedron (Fig. 100), and also the twelve edges of the cube (Fig. 32). The cube-planes truncate the solid angles at the six axial terminations of the rhombic dodecahedron.

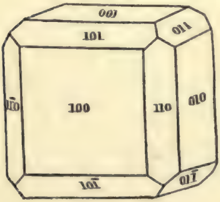


FIG. 32.

The groups of planes occurring in each octant in the six-faced and three-faced octahedrons and in the icositetrahedron are found modifying the eight solid angles of the cube, and therefore also the eight solid angles of the rhombic dodecahedron in which the axes of 3-fold symmetry emerge

(Fig. 121). The four-faced cube produces a bevelled modification of the edges of the cube, and the three-faced octahedron similarly treats those of the octahedron.

Class II (30).—Three planes of symmetry perpendicular to one another, and intersecting in three axes of 2-fold symmetry which are equal in length. These are used as the crystallographic axes. Four axes of 3-fold symmetry arranged as in Class I.

Dyakis-dodecahedron (Fig. 33).—{hkl} or {khl}, the index *h* being greater than *k*. The symmetry here requires only three planes in each octant, or twenty-four in all. These are similar trapezoids, each having another parallel to it. Positive and negative forms are recognised, convertible into one another by rotation through 90°.

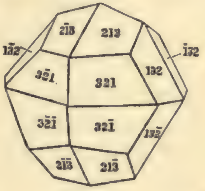


Fig. 33.

Pentagonal Dodecahedron (Fig. 34).—{hko} or {kho}, the index *h* being greater than *k*. This form limits the preceding one, when $l = 0$. Planes in adjacent octants of the dyakis-dodecahedron merge, and a form results bounded by twelve pentagonal faces. The planes (hkl) and (hk$\bar{l}$), for instance, become a single vertical pentagonal plane (hko). One side of each pentagon is longer than the others. The conspicuous feature of the form is the alternation of four of these longer sides in upright and horizontal positions as the crystal is rotated about the vertical axis. When the line in which the *a*-axis terminates is vertical, the form is styled positive, {hko}; when it lies horizontally, the form is negative, {kho}.

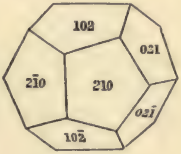


Fig. 34.

These two forms take the place in this class of the six-faced octahedron and the six-faced cube. The other forms of the class are the same as the remaining forms in Class I, the cube, one of the limiting forms of {hko}, being often combined with the pentagonal dodecahedron, its six planes truncating the longer edges of the pentagons (Fig. 78). The pentagonal dodecahedron truncates the twelve edges of the cube; but this combination is distinguished from that of the rhombic dodecahedron and the cube by the fact that the truncating planes are not equally inclined to two of the axes. Pyrite belongs to this class.

CLASS III (31).—Six planes of symmetry, which are the diagonal planes of symmetry in the cube. Three axes of 2-fold symmetry perpendicular to one another and equal in length; these are used as the crystallographic axes. Four axes of 3-fold symmetry, as in Class I.

The class differs, then, from Class II in omitting the three principal planes of symmetry containing the crystallographic axes, and retaining the diagonal ones, which are omitted in that class. The result is a number of forms of bisphenoidal type.

Hexakis-tetrahedron $\{hkl\}$ or $\{h\bar{k}l\}$.—A form something like a tetrahedron (see below), with a pyramid of six similar scalene triangles on each of its faces, or twenty-four faces in all. The negative form is $\{h\bar{k}l\}$.

Triakis-tetrahedron $\{hkk\}$ or $\{\bar{h}kk\}$.—Three isosceles triangular faces represent each face of the tetrahedron; twelve faces in all. In the quadrant of $\{hkk\}$ which has all the indices positive, one face lies above, with its longer edge horizontal, and two lie below it.

Deltoidal Dodecahedron $\{hhl\}$ or $\{h\bar{h}l\}$.—Three deltoidal faces represent each face of the tetrahedron; twelve faces in all. In the quadrant of $\{hhl\}$ which has all the indices positive two faces lie above and one below.

Tetrahedron (*Bisphenoid*) $\{111\}$ or $\{1\bar{1}1\}$.—The bisphenoid of the cubic system is bounded by four equilateral triangles. The two forms are convertible into one another on rotation, as in the tetragonal system, the negative one being $\{1\bar{1}1\}$. The three units here, of course, represent equal intercepts on all the axes, as in the octahedron.

The other forms in this class are those of Class I that are not represented by the above tetrahedral types, namely, the rhombic dodecahedron, the four-faced cube, and the cube. In combinations, the cube truncates the edges of the tetrahedron (Fig. 35). The positive and negative tetrahedra cut off each other's solid angles, and, when developed in the same proportions, would produce an octahedron (Fig. 36). The true symmetry of a cube of this class may be revealed by the presence of the faces of $\{111\}$ on four of its solid angles

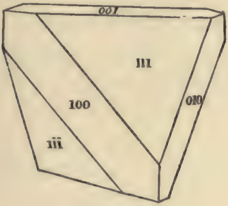


FIG. 35.

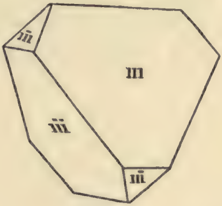


FIG. 36.

only. Diamond belongs to this class, and its apparent hexakis-octahedral forms consist of $\{hkl\}$ and $\{h\bar{k}l\}$ in combination, while its octahedra consist of $\{111\}$ and $\{1\bar{1}1\}$.

CLASS IV (29).—In this remarkable class, all the thirteen axes of symmetry of Class I are present, but there are no planes of symmetry. The characteristic form is the *Pentagonal Icositetrahedron* (Fig. 37), $\{hkl\}$ or $\{khl\}$, bounded by twenty-four irregular pentagons, no two sides of which are equal. The two forms are truly left-handed and right-handed, being enantiomorphous. Cuprite occurs in this class, though its crystals usually exhibit only the other forms of the class, such as the octahedron and the rhombic dodecahedron, which impart an appearance of symmetry higher than that attained by the crystalline structure.

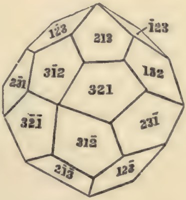


FIG. 37.

CLASS V (28). — Three axes of 2-fold symmetry perpendicular to one another and equal in length, and used as the crystallographic axes. Four axes of 3-fold symmetry, as in Class I. No planes of symmetry.

Tetrahedral Pentagonal Dodecahedron $\{hkl\}$, $\{khl\}$, $\{h\bar{k}l\}$ or $\{k\bar{h}l\}$.—The form is bounded by twelve irregular pentagons, and there are two enantiomorphous pairs. The members of the first pair, $\{hkl\}$ and $\{khl\}$, are styled respectively left and right positive forms; those of the second pair are left and right negative forms.

Hexagonal System.

The arrangement of the three equivalent lateral axes in this system on the Bravais-Miller basis has been stated on pp. 42 and 47. Few rock-forming minerals crystallise in this system, apatite being probably the most important.

CLASS I (27).—Six planes of symmetry intersecting at 30° to one another in an axis of 6-fold symmetry, which is set vertical and is used as the *c*-axis. A horizontal plane of symmetry, and six horizontal axes of 2-fold symmetry, formed by its intersection with the vertical planes of symmetry. Three of these horizontal axes, at 60° to one another, are selected as a_1, a_3, and a_2. We may remember (p. 50) that the sum of the first three indices always = 0. For plans of the forms see Fig. 38.

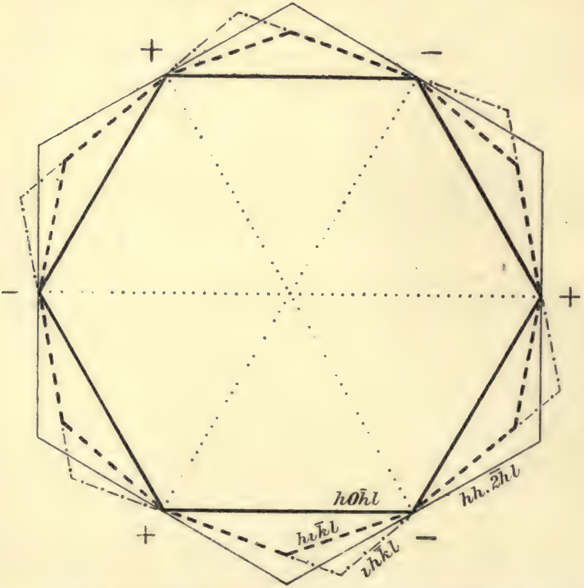


FIG. 38.—Horizontal sections of forms of the hexagonal system. The lines of round dots represent the lateral axes.

Dihexagonal Bipyramid $\{hi\bar{k}l\}$.—Like the ditetragonal bipyramid, this form is bounded by similar scalene triangles, twenty-four in this case; the intercepts on the three lateral axes cannot be incommensurable, and hence the form with a regular dodecagon as its plan and isosceles triangles as its faces is excluded in nature. It is obvious that the ratio of two of the lateral intercepts determines the third intercept. $\{12\bar{3}1\}$ is a typical form. The three lateral axes emerge in alternate lateral solid angles.

Hexagonal Bipyramid of the First Order (Fig. 38) $\{h0\bar{h}l\}$.—When in $\{hi\bar{k}l\}$ $i = 0$, h and k become equal. The twenty-four planes of the dihexagonal form pass into only six above and six vertically below them, and these are isosceles triangles. Two of these planes face the observer, an axis emerging at every lateral solid angle.

Hexagonal Bipyramid of the Second Order $\{hh.\overline{2h}.l\}$.—When in $\{hi\bar{k}l\}$ the intercepts on a_1 and a_2 are equal, that on a_3 becomes half their length (see Fig. 38). If the first index is the unit 1, the first three indices are then $11\bar{2}$. $\{11\bar{2}1\}$ is a characteristic form. A polar edge of the upper pyramid faces the observer, with one belonging to the lower pyramid below it, and the three lateral axes emerge in the centres of the lateral edges.

When the index $l = 0$, we have the three corresponding prisms:—

Dihexagonal Prism $\{hi\bar{k}0\}$.

Hexagonal Prism of the First Order $\{h0\bar{h}0\}$, written as $\{10\bar{1}0\}$.

Hexagonal Prism of the Second Order $\{h0.\overline{2h}0.\}$, written as $\{10\bar{2}0\}$. This form represents the vertical pinacoids of other systems.

Basal pinacoid pair $\{0001\}$.

Beryl is a good example of this class.

Class II (26).—Six planes of symmetry intersecting at 30° to one another in an axis of 6-fold symmetry, which is set vertical and is used as the c-axis. No horizontal plane or axes of symmetry.

The forms in this class are the upper and lower halves of the bipyramids of Class I, the three complete prisms, and the upper and lower basal planes, $\{0001\}$ and $\{000\bar{1}\}$.

CLASS III (25).—One axis of 6-fold symmetry, which is set vertical and used as the *c*-axis, perpendicular to a plane of symmetry. The forms are recognisable as distinct from those of Class I only in combinations. As in Class III of the tetragonal system, right-handed and left-handed forms occur, convertible into one another on rotation about the vertical axis.

Third Order Hexagonal Bipyramids.—$\{hi\bar{k}l\}$, the right-handed form; $\{k\bar{i}\bar{h}l\}$, the left-handed form (shown in Fig. 38).

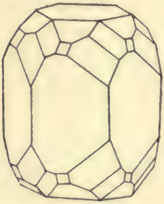


FIG. 39.—Crystal of apatite (after Groth).

Third Order Hexagonal Prisms.—$\{hi\bar{k}o\}$, right-handed; $\{k\bar{i}\bar{h}o\}$, left-handed.

These take the place of the dihexagonal forms in Class I, and the other possible forms are the same as in that class.

Example (Fig. 39).—A crystal of Apatite showing a first order prism, two first order bipyramids, a second order bipyramid, the third order bipyramid $\{21\bar{3}1\}$, and basal planes.

CLASS IV (23).—The axis of 6-fold symmetry is alone present. Owing to the absence of the horizontal plane of symmetry, the forms are related to those of Class III as those of Class II are to those of Class I. The upper or lower halves of third-order bipyramids occur as the typical *pyramids* of this class, the crystals being hemimorphic on the vertical axis. These forms and the corresponding prisms are recognisable from those of Class II only in combinations.

CLASS V (24).—All the seven axes of symmetry of Class I are present, that of 6-fold symmetry being set vertical; but there are no planes of symmetry. The forms in this class with the symbols $\{hi\bar{k}l\}$ and $\{k\bar{i}\bar{h}l\}$ are distinct from those of all other classes. They are respectively the *right-handed* and *left-handed hexagonal trapezohedron*, bounded by twelve trapezoids. See p. 200.

Trigonal System.

The occurrence of quartz and calcite in this system suffices to give it great importance. As explained on p. 43, the same scheme of axes will here be utilised as was adopted for the hexagonal system.

CLASS I (22).—Three planes of symmetry intersecting at 60° to one another in an axis of 3-fold symmetry, which is used as the *c*-axis. Perpendicular to these, a horizontal plane of symmetry, forming, by its intersections with the vertical planes, three horizontal axes of 2-fold symmetry. The lines bisecting the angles between these are utilised as the three lateral crystallographic axes.

Ditrigonal Bipyramid.—$\{hi\bar{k}l\}$ and $\{\bar{h}\bar{i}kl\}$, positive and negative forms.—Bounded by six scalene triangles above, and six arranged vertically below them, the angles of the six-sided plan being only alternately equal. The lateral axes emerge one in each lateral edge and not perpendicular to it. (See Fig. 40.)

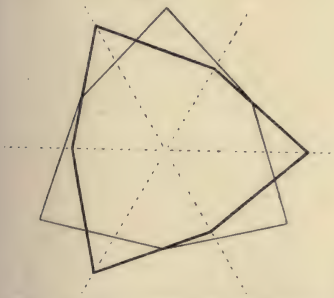


FIG. 40.—Horizontal sections, showing the relations of the axes (dotted lines) to the planes of the ditrigonal bipyramid or prism in Class I (thin outline); and of the ditrigonal prism in Class VI (thick outline).

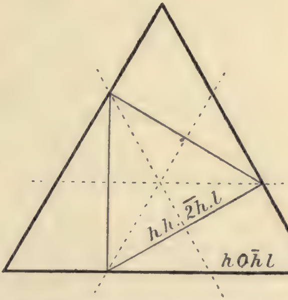


FIG. 41.—Horizontal sections, showing the relations of the axes (dotted lines) to the lateral edges of the first and second order trigonal bipyramids. The former occurs in Classes I and III, and the latter in Classes III and VI, being common in quartz.

Trigonal Bipyramid of the First Order.—$\{h0\bar{h}l\}$ positive, and $\{0h\bar{h}l\}$ negative.—In the horizontal section (Fig. 41), two axes are seen to emerge in each lateral edge, and these edges are respectively perpendicular to the vertical planes of symmetry. The form is bounded by six isosceles triangles.

When $l = 0$, the corresponding *ditrigonal* and *trigonal first order prisms* result (Fig. 42). The other forms in the class are the *basal pinacoid pair* $\{0001\}$ and the *hexagonal second order bipyramid* and *prism.*

Benitoite, $BaTi(SiO_3)_3$, is the only known mineral crystallising in this class.

CLASS II (20).—Three planes of symmetry intersecting at 60° to one another in an axis of 3-fold symmetry, which is used as the *c*-axis. No horizontal plane or axes of symmetry. Two types of *pyramid* occur, the *ditrigonal* positive and negative pair, and the *trigonal first order* pair, and these correspond with the four bipyramids of the preceding class. Either the upper or lower halves of these bipyramids may be here represented. The corresponding *prisms* occur, and the *basal planes* $\{0001\}$ and $\{000\bar{1}\}$ as independent forms.

The class is of geological importance from the occurrence in it of tourmaline, the crystals of which are classical examples of hemimorphism. In Fig. 42 a crystal of tourmaline is shown, terminated above by a positive and a negative first order pyramid and below by the same forms, but with different intercepts.

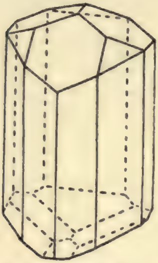


FIG. 42.—Crystal of tourmaline (after Groth).

CLASS III (19).—One axis of 3-fold symmetry, which is set vertical, perpendicular to a horizontal plane of symmetry. No other elements of symmetry. This corresponds with Class III in the hexagonal system, and its characteristic form is the *third order trigonal bipyramid*. This has four variations, right positive $\{h\bar{i}kl\}$, left positive $\{k\bar{i}\bar{h}l\}$, right negative $\{\bar{h}\bar{i}kl\}$, and left negative $\{\bar{k}ihl\}$. The sections in Fig. 49 are constructed so as to serve also in illustrating the trapezohedra of quartz crystals, the form being that in which $h = 5$, $i = 1$, and $k = 6$.

When $h = i$, $k = 2h$, and we have the *second order trigonal bipyramid*. This has a right-hand or positive variety $\{hh.\overline{2h}.l\}$ and a left-hand or negative variety, $\{2h.\bar{h}\bar{h}l\}$. Each of the lateral axes in this form unites a lateral solid angle with the centre of the lateral edge opposite it, instead of lying parallel to a lateral edge, as in the first order form. (See Fig. 41.)

Prisms corresponding with these six bipyramids occur in this class ; also the *first order trigonal bipyramid*, positive and negative varieties, and the two corresponding *prisms*. Also the *basal pinacoid pair*.

No representative of this class is yet known.

CLASS IV (21).—Three planes of symmetry intersecting at 60° to one another in an axis of 3-fold symmetry, which is used as the *c*-axis. Three horizontal axes of 2-fold symmetry, bisecting the angles between the planes of symmetry. These are used as the lateral crystallographic axes. No horizontal plane of symmetry.

This class possesses great importance from the occurrence in it of calcite, the commonest crystallised form of calcium carbonate.

Ditrigonal Scalenohedron.—$\{hi\bar{k}l\}$, positive; $\{\bar{h}\bar{i}kl\}$, negative (Fig. 43).—This form is so well known that it is always indicated when "the scalenohedron" is mentioned without a qualifying adjective. It is bounded by six scalene triangles above and six below, the upper ones not being the mirror-images of those below, owing to the absence of the horizontal plane of symmetry. The lateral axes emerge in the centres of six lateral edges, which form a zigzag series, crossing the horizontal plane of the lateral axes. Variations in the intercept on the vertical axis allow of a series of scalenohedra, from squat to extremely elongated forms, without any variation of the intercepts on a_1, a_2, and a_3. The limiting forms for such variations on the *c*-axis are the dihexagonal prism, when the index $l = 0$, and the rhombohedron. The particular rhombohedron that arises is determined by the indices *hik*, which decide the inclination of the lateral edges of the scalenohedron to the horizontal plane. This point will now receive further explanation.

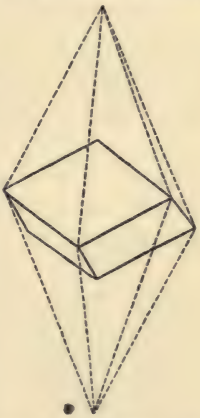


FIG. 43.—Positive ditrigonal scalenohedron (dotted outline) with corresponding positive rhombohedron inscribed within it. The lateral edges of both forms are seen to be identical.

Rhombohedron of the First Order.—$\{h0\bar{h}l\}$, positive; $\{0h\bar{h}l\}$, negative (Figs. 43, 44, and 45).—When in the scalenohedron $\{hi\bar{k}l\}$ $i = 0$, then $k = h$, and the twelve planes merge into six, three above alternating with three below. At the same time, the intercept on the vertical axis is shortened, so that the resulting form is bounded by six rhombuses, each polar edge being parallel with two of the lateral edges of the form. Every scalenohedron may thus have a rhombohedron of a particular vertical height inscribed within it, and this is the only rhombohedron that can be evolved from it (Fig. 43). On the other hand, for every rhombohedron an infinite series of scalenohedra may be geometrically evolved, by drawing lines from the lateral solid angles of the rhombohedron to meet one another in any point on the vertical axis above the apex of the rhombohedron.

The rhombohedron resembles a cube deformed by being pushed over in the direction of one of the diagonals of its upper or lower faces, and then set with the surviving axis of 3-fold symmetry upright. Hence the cube itself is a possible member of the series of rhombohedra. It is a rhombohedron with an axial ratio of 1 : 1·2247. Its symmetry, however, is too high for substances that crystallise in the trigonal system, and rhombohedra are accordingly *acute*, where $a : c = 1$: some value greater than 1·2247, or *obtuse*, where $a : c = 1$: some value less than 1·2247.

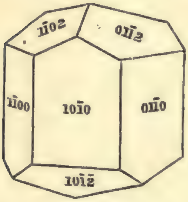


FIG. 44.—Crystal of calcite, with negative rhombohedron, and first order hexagonal prism.

The positive and negative forms of the rhombohedron are recognisable in combination with one another or with hexagonal prisms; in the positive rhombohedron one face appears above, fronting the observer, with an edge below it. The edge is above in the negative form, with a single face below it. (Figs. 43 and 44.)

The scalenohedron and rhombohedron represent in Class III the bipyramids of Class I. The other forms in Class III are the *dihexagonal prism*, and, of far more common occurrence, the *hexagonal prisms of the first and second orders*. Also the *basal pinacoid pair* {0001}.

The combinations in this class, which are so easily studied in the forms of calcite, present features of great variety. A rhombohedron may be set in either a positive or negative relation to the observer; but this will not alter the character of a hexagonal prism associated with it, which remains determined by the rhombohedron as first or second order. A rhombohedron and a first-order hexagonal prism yield a form (Fig. 44) with somewhat shield-like prismatic faces, a horizontal edge at the upper end of the face having two edges forming a downward-pointing angle below it, and *vice versâ*. When the second order prism occurs with the rhombohedron, the planes of the latter intersect those of the prism in a zigzag series of edges parallel with the polar edges of the rhombohedron (Fig. 45).

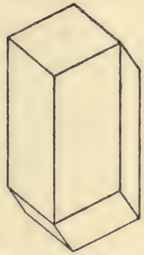


FIG. 45.—Positive rhombohedron and second order hexagonal prism.

The polar edges of a rhombohedron may be evenly truncated by the faces of a rhombohedron of opposite sign, in which case, the axial ratio of the first rhombohedron being $a : c$, that of the truncating one is $a : \frac{c}{2}$. Thus $\{10\bar{1}1\}$ can have its polar edges evenly truncated by the negative rhombohedron $\{01\bar{1}2\}$.

Combinations of rhombohedra and scalenohedra are common in calcite (Fig. 91). In the scalenohedron combined with the hexagonal prism of the first order, shield-like prismatic faces are again apparent (Fig. 46). The second order prism truncates the lateral edges of the scalenohedron.

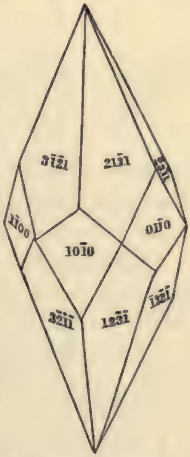


FIG. 46.—Crystal of calcite, with scalenohedron and first order hexagonal prism.

CLASS V (17).—One axis of 3-fold symmetry and no other element of symmetry, except that each plane has another parallel with it on the opposite side of the centre of the crystal. Class V is related to Class IV as Class III is to Class I. *Third-order rhombohedra*, $\{hi\bar{k}l\}$ etc., are the characteristic forms. Right and left handed *second order rhombohedra* also occur in this class. These two series of forms are recognisable only in combinations. Dolomite is now known to possess this low symmetry. Third order rhombohedra occur in crystals of dioptase.

Class VI (18).—One axis of 3-fold symmetry perpendicular to three axes of 2-fold symmetry, which intersect at 60°. No planes of symmetry. The axes of symmetry are used as the four crystallographic axes.

Quartz and cinnabar belong to this class.

The distinctive forms are four *trigonal trapezohedra* (compare Class V in the tetragonal system) bounded by six faces; the lateral axes emerge in the central points of the lateral edges. The right-handed positive form is $\{hi\bar{k}l\}$, and the left-handed positive form $\{k\bar{i}\bar{h}l\}$ is enantiomorphous with it (see Figs. 47 and 48). A second pair of enantiomorphs is furnished by the right-handed negative form $\{\bar{h}\bar{i}kl\}$, and the left-handed negative form $\{\bar{k}ihl\}$. The three upper planes of each trapezohedron have the same relations to the Bravais-Miller lateral axes as the third order bipyramid planes shown in plan in Fig. 49.

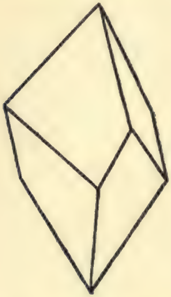


Fig. 47.—Left-handed trigonal trapezohedron (after Tutton).

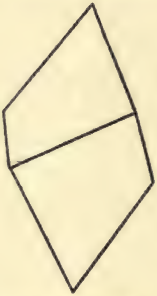


Fig. 48.—Right-handed trigonal trapezohedron (after Tutton).

The frequent occurrence of these trapezohedra in crystals of quartz give them especial importance. They indicate the low degree of symmetry in this mineral, and the presence of right-handed or left-handed forms provides external evidence of the right-handed or left-handed optical character of the crystal (p. 128).

The other forms possible in this class are the two *second order trigonal bipyramids* (see Class III); the two *first order rhombohedra* (which in combination represent the first order hexagonal bipyramid); the two *ditrigonal prisms* (which in this class have the lateral axes emerging in the centres of the vertical edges, and not as in Class I; see Fig. 40); the two *second order trigonal prisms* (which in combination represent the second order hexagonal prism); the *first order hexagonal prism;* and the *basal pinacoid pair.*

Crystals of quartz commonly exhibit a first order hexagonal prism combined with a positive and negative rhombohedron. Six small planes of rhomboid form occur frequently on the alternate solid angles formed by the junction of the planes of the rhombohedron and the prism, three being above and three symmetrically below them. These represent a second order bipyramid. Below these in the upper part of the crystal are three planes of a trapezohedron, which indicate by their inclinations the absence of all planes of symmetry, and above the corresponding bipyramid planes in the lower part are three corresponding trapezohedron planes.

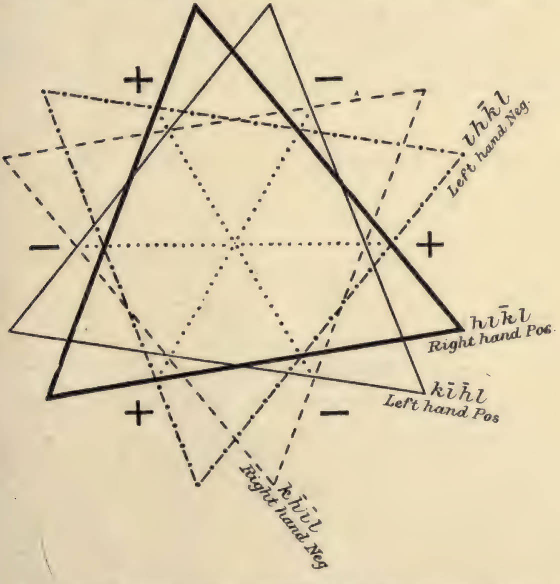


FIG. 49.—Horizontal sections showing the relations of the axes (dotted lines) to the lateral edges of the four third order trigonal bipyramids (Class III), and to the three upper planes of the four trigonal trapezohedra (Class VI). *hik* in the form selected = 516, as in the common form in quartz.

If, in the upper part of the crystal, these accessory planes, bipyramidal or trapezohedral or both, occur at the upper right-hand corner of a prism plane, the crystal is right-handed; when they are at the upper left-hand corner, it is left-handed (Fig. 86).

CLASS VII (16).—One axis of 3-fold symmetry and no other element of symmetry. The forms are distinct from those of Class V by the fact that the planes do not occur in pairs the members of which are parallel to one another. The characteristic forms, recognisable from those of Class II only in combination, are *third order* and *second order trigonal pyramids*. Crystals in this class are of course hemimorphic on the vertical axis.

CHAPTER V

TWIN CRYSTALS AND CLEAVAGE

Twin Crystals.

THE consideration of *twinning* in crystals has been deferred till now, since the subject, though a general one, is most conveniently illustrated by examples from the several crystallographic systems. In all minerals crystals may arise which have been built up in two portions, so that the molecular structure in one portion is exactly reversed in position with regard to the structure in the other portion. Sometimes the crystal resembles two half crystals that have been joined together in reversed positions, so that one half must be turned through 180° before it can be brought into correspondence with the other half (Fig. 50). Sometimes it seems as if two crystals had grown into one another (*interpenetrant twinning*), in what we may call the twin relation, a rotation of one crystal through 180° being required to bring the two portions into crystallographic coincidence. In other cases, two enantiomorphs have grown up side by side, attached or interpenetrant, with their crystallographic axes respectively parallel. It is obvious that in such twins the two parts will not coincide upon rotation.

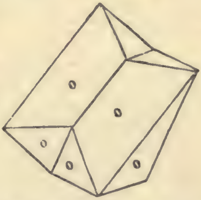


FIG. 50. — Octahedron twinned on a plane of the same form.

In all cases of twinning but those in the cubic system, optical tests show that there is a surface in the joint crystal, which may be a plane or which may be step-like or irregular, on opposite sides of which the crystal has developed with a different orientation. This surface, when a plane, has been called the *plane of composition.* The positions of cleavage-planes in the two parts may indicate the position of the dividing surface in twins of the cubic system.

The two portions of the crystal are like reflections of one another (Fig. 51). The plane across which the reflection takes place is called the *twin-plane*, and is always a possible plane of the mineral species that has given rise to the twin crystal. It is a plane of symmetry added to the joint crystal, the simple type of which may possibly possess no planes of symmetry. It will be seen that in cases of parallel growth (p. 26) the parts of the joint crystal may be regarded as steps in the building up of a crystal of larger size, with its structural lines and planes similarly oriented throughout. Parallel growth is thus distinct from twinning, since there is no reversal of structural features in the components.

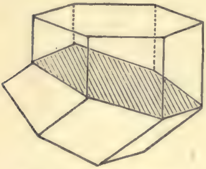


FIG. 51.—Hexagonal prism of the first order twinned on a plane of a pyramid of the same order.

In most twin crystals, there is a line about which one portion of the twin may be conceived to be rotated and brought into crystallographic parallelism with the other portion, the required rotation being always 180°. This line is called the *twin-axis*, and is a possible edge of the crystal. It is perpendicular to the twin-plane. It is clear that twins formed by the union of enantiomorphs have no twin-axis.

Interpenetrant twinning obeys the same laws as the more obvious type. The two or more crystals associated are found to be regularly and not fortuitously intergrown. If one crystal could be detached from the other, either a line could be found about which it could be rotated through 180°, so as to be brought into the same crystallographic position as the other crystal; or else a plane could be found across which it would appear as the reflection of the other crystal. Hence such twins possess a twin-axis, or a plane of reflection, like ordinary twins.

The interpenetrant cubes of fluorspar in Fig. 52 are twinned on an octahedral plane; that is to say, if one of them could be detached and maintained in its crystallographic position relative to the other, it would be found to be a reflection of the other across a plane which is that of an octahedron. If the two parts of the interpenetrant twin of orthoclase in Fig. 111 could be pulled asunder and set end to end, with their end prism edges touching and their *b*-axes parallel and in the same horizontal plane, one of them would be found to be the reflection of the other, across a plane parallel to the *b* and *c* axes. This is an orthopinacoid-plane, and rotation through 180° about a line perpendicular to it brings the two crystals into the same crystallographic position. We may say, then, that in such twins the twin-plane is the orthopinacoid. Rotation of one of the crystals about the *c*-axis would produce the same result. This axis is thus a twin-axis.

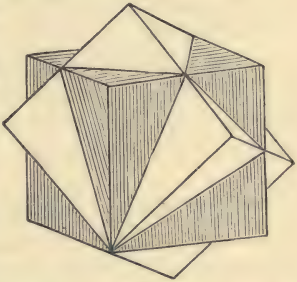


FIG. 52.—Interpenetrant twin of fluorspar.

In interpenetrant twins, *re-entrant angles* are usually strongly marked; and this feature, which is absent from untwinned crystals (p. 26), is present in the great majority of twins. In unnotched twins, optical tests may be the easiest means of detecting the true structure; but these fail in the cubic system, and goniometry is the surest guide.

When more than two individuals are united in the twin relation, the twinning is said to be *repeated*. Triclinic felspars are usually built up of lamellæ oriented alternately 180° apart. Since this arrangement causes the regular planes of fracture (cleavage-planes) that are parallel to the basal pinacoid to slope differently in adjacent layers of the repeated twin, one set may catch the light on fractured surfaces while the other remains dull. *Twin-bands* thus run across the crystal and reveal its nature, though they may be so delicate as to require looking for with a lens (Fig. 106).

Fracture and Cleavage.

The varying modes in which minerals behave under a blow have been referred to under the head of tenacity (p. 11). But the nature of the fractured surface is often closely related to the crystalline structure of the substance. Irregular surfaces of fracture may be fairly *smooth;* or *hackly*, when showing a series of little knobs and hollows, like a broken metal bar; or *splintery*, when a fibrous structure is revealed; or *conchoidal*, when a curved and wavy surface is produced, like that of the inside of a pearly shell. Glass and quartz have conchoidal fracture.

But in very many cases regular surfaces arise, which depend upon the internal grouping of the molecules in the crystal. The mineral parts asunder, in fact, more readily along certain planes than along others, and these planes are called planes of *cleavage*. They are always possible planes of the mineral in its crystallised state, and serve as valuable guides to the orientation of a crystal-fragment, and often in its identification. The angle between two series of cleavage-planes in the same crystal is often more useful for determinative purposes than any external feature.

It was the regularity of cleavage that led Haüy to the discovery of the law of rational intercepts, since it gave him the conception that a crystal was built up of similar ultramicroscopic forms, whatever planes might appear upon its surface. He was handling a group of crystals of calcite in the collection of a friend, when a piece broke off along a cleavage-plane. He asked leave to carry away this fractured crystal; he broke it up, and many others afterwards, observing that various mineral species gave rise to a characteristic *solids of cleavage*, which might be regarded as their fundamental forms. The Swedish mineralogist, Bergmann, one of Haüy's contemporaries, also suggested, from his observations on cleavage, that calcite might be built up of little natural bricks having the same form as the solid produced by cleavage. Haüy's experiments were not approved by Romé de l'Isle, who called him a *brise-cristaux* for relying so greatly on internal structure; yet in recent years all reasoning as to the properties of crystals has been based upon conceptions of the geometrical grouping of molecules, and of atoms within the molecules, so as to build up the structures that we know as crystals.

Calcite – rhombohedron

The cleavage-planes of calcite form three series, equally inclined to a line, which proves to be the axis of 3-fold symmetry of the crystal from which the cleavage-fragment is derived. The cleavage-fragment is, in fact, a rhombohedron, since, whatever its proportions as it breaks out of the crystal, angular measurements show it to possess rhombohedral symmetry.

The three series of cleavage-planes in calcite are thus of equivalent value; and this feature of cleavage is found to prevail in other minerals. Where in monoclinic or rhombic crystals the cleavage is parallel to a prism-face, two equivalent cleavages are present; but one alone may occur in triclinic crystals, where each pair of prism-planes is an independent pinacoid. A cleavage parallel to an octahedral face implies the existence of four such cleavages. Fluorspar, which commonly crystallises in cubes, furnishes the octahedron as its "solid of cleavage." Rock-salt, however, which crystallises also in cubes, breaks parallel to the cube-faces, possessing thus three equivalent cleavages perpendicular to one another. Garnet possesses six equivalent cleavages, each parallel to one of the pairs of faces of the rhombic dodecahedron.

salt — cubes

Two cleavage-systems may occur in the same crystal. The felspars, for instance, break parallel with the *a*-pinacoid and also with the basal plane, and the angle between these cleavages is of great determinative value.

Felspar ha
2 cleavage planes.

Cleavage varies greatly in its approach towards perfection in various minerals. The micas can be split along a perfect basal cleavage into flexible plates far thinner than foreign note-paper. The cleavage of calcite is almost as good, but the three series of planes develop little brick-like forms instead of plates. The cleavage of garnet and augite is far less readily demonstrated. Under the microscope, in thin sections, cleavage-planes are often revealed as striæ or fine cracks running regularly across the crystal, since stresses in the earth have caused the minerals to yield along these natural planes of weakness.

The absence of cleavage in quartz is probably connected with its low symmetry, and its conchoidal fracture becomes a determinative character.

CHAPTER VI

OPTICAL CHARACTERS

THE optical characters of minerals were studied by Brewster and others at the opening of the nineteenth century, through the use of comparatively large transparent specimens and apparatus which would be regarded as costly at the present day. Thanks to the work then done, observations can now be made even on minute fragments of minerals under the microscope, and the fundamental laws that were patiently established by a long series of experiments can be applied with confidence in determinative mineralogy.

Definitions.

It may be well to remind ourselves of some of the terms used in the description of optical phenomena. The impression that we style light is regarded as due to the disturbance of the ether which permeates all space and all bodies. For convenience, this ether may be considered as consisting of particles, and these vibrate to and fro under the light-impulse on paths at right angles to the line along which the light-ray is propagated. At one point (Fig. 53) a particle A at a

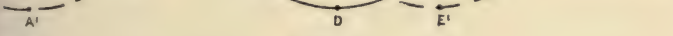


FIG. 53.

certain moment lies exactly on the line of propagation. Farther on, a particle B is at the farthest point of its swing on one side of the line. At an equal distance farther on, a particle C lies on the line. At an equal distance farther along the line, a particle D is at the farthest point of its swing on the opposite side of the line to B. At an equal distance, again, farther on, a particle E lies on the line. Since these particles all swing across the line of propagation through paths of equal length, the conditions here postulated as occurring at a certain moment are shifting continuously along the line. B and D are about to move along the shortest path towards the line; from B to D all the particles are ascending at the moment for which the diagram is drawn, while from D to F they are descending. By the time that B and D are on the line, which they reach simultaneously, C will have risen to its full distance above the line. The crest of the wave thus propagated will now have moved so much forward. The particles A and E will by this time have moved to the lowest part of their swing, and the trough of the wave will have also moved forward. Particles which are in the same position in regard to the line of propagation and are both moving from it or towards it in the same direction are said to be in the same *phase*. A and E are thus in the same phase; so also are B and F. But A and C are in opposite phases, since A is descending while C is ascending.

The distance between two particles in the same phase is the *wave-length* for the particular ray. The length of the path through which each particle swings is the *amplitude* of the ray. It is clear that amplitude can be increased or decreased without affecting wave-length. Increased amplitude merely increases the intensity of the light-impression. In ordinary media, the amplitude is reduced gradually as the wave-motion is transmitted to a distance. If the amplitude is greatly reduced, the eye may not be able to appreciate the presence of a light-vibration.

The time required for a particle to go through all the phases of its swing, that is, to start from the line of propagation, move to its end-point at one side, cross the line to the opposite end-point, and return to the line, is styled the *period.* During this period the crest or trough of a wave has advanced one wave-length.

Light-waves are propagated with various velocities. The *velocity* is the distance traversed by the light in unit time. If the wave-length remains constant and the velocity is increased, the time occupied by each vibration must be reduced. *The period of a light-wave may thus be expressed as the wave-length divided by the velocity.* If, therefore, the period remains the same, although there is an increase in velocity, the wave-length must become lengthened simultaneously with the increase in the velocity.

The rapidity with which the vibrations take place, that is, the period of the ray, depends on the rapidity of the vibrations at the source of the light. If the source remains unchanged, the period remains so also, whatever substances are traversed by the light-ray. But the velocity is variously altered during the passage of a ray through various media. In such cases, it is clear that the wave-length also becomes altered, resuming its former value on emerging again into the original medium.

Rays are of various *colours.* In space, that is, in a vacuum, the velocity of rays of all colours is the same, and the colour may be said to depend upon the wave-length, red light having the longest wave-length and violet the shortest among the waves appreciable by the human eye. But light of any particular colour retains that colour while traversing and on emerging from colourless media in which it has been bent out of its course by refraction. Such bending implies alteration of velocity, and therefore, as above shown, of wave-length. Hence colour does not in reality depend upon wave-length, but upon the wave-length divided by the velocity, that is, upon the period. The period for violet rays in space is about half that for red rays.

A translucent medium, such as a crystal, may become practically opaque if a sufficient thickness is employed. In traversing the crystal, the light-energy has become greatly reduced, and the emerging rays have consequently a much-lessened amplitude. When white light, which consists of rays of various colours, emerges from a medium as coloured light, it is clear that this medium has effected a reduction in the amplitude of the rays of some colours more rapidly than of those of the surviving colours. This is the phenomenon of *absorption.*

In an ordinary ray of light, the vibrations are conceived as taking place in all planes, rapid changes of plane occurring as the waves move forward. Light may, however, have its vibrations all reduced to one plane. Such light is styled *plane-polarised light*, or merely "polarised light." The plane in which its vibrations take place may be called its *vibration-plane.* For experiments in crystal-optics, polarised light is ordinarily employed.

If two polarised rays from the same source,[1] *of the same wave-length, and with their vibration-planes parallel, are propagated along the same line, interference occurs*, which may be either helpful or the reverse. If the rays are propagated in the same phase, a wave will be produced with an amplitude which is the sum of the amplitudes of the two rays; but, if the phases are different, the resulting ray will have an amplitude less than this sum, or even less than that of either of the two rays regarded independently. If the two rays are in exactly opposite phases, the stimulus given to an ether-particle by the propagation of one of the rays will be opposed by the stimulus imparted by the other, and the resulting amplitude will be the difference of the amplitudes of the two rays. *If the two plane-polarised rays are equal in amplitude and opposite in phase, the energy will no longer be manifested as light*, since the light-vibrations cannot take place. Two plane-polarised rays of the same amplitude and wave-length can thus, under certain circumstances, be caused to annihilate one another.

If a ray of light passes from a medium of a certain density to one of greater density, and strikes the surface of junction of the two media obliquely, it is in all cases, on entering the medium of greater density, bent out of its original course and towards the normal to the surface of junction. On again emerging into the original medium at a surface parallel with that by which it entered the second medium, it resumes its original course. Should the second medium be of less density than the first, the ray is bent away from the normal to the surface of junction on entering the second medium, and as much towards the normal on emergence. This alteration of the course of the ray is styled *refraction*. It is always accompanied by some loss of light, owing to *reflection* taking place at the same time when a bundle of rays falls on a refracting surface. The angle made by the oblique ray falling on the surface with the normal to the surface is the *angle of incidence*, and the plane containing the ray and the normal is the *plane of incidence*. The reflected ray makes an angle with the normal equal to that of incidence, and also lies in the plane of incidence.

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[1] See L. Fletcher, "The Optical Indicatrix" (1892), 83–5, or *ibid.*, *Min. Mag.*, **9** (1891), 359–361.

The angle made with the normal by the refracted ray is called the *angle of refraction*, and the amount of refraction is measured by dividing the sine of the angle of incidence by the sine of the angle of refraction. This value is the *refractive index* for the two media in association, and for the particular colour of light employed. Where one medium is commonly employed for all experiments, such as the air, the value may be styled the refractive index of the second medium. In non-crystalline substances, such as water and glass, and in minerals of the cubic system, the refractive index is found to be the same, whatever the direction of the incident ray and of its passage through the substance. In such cases only one refracted ray is formed from the incident ray (*single refraction*), and this lies in the plane of incidence. Such bodies are said to be *isotropic*.

But in minerals of all systems other than the cubic two rays are formed (*double refraction*), except where the ray travels along certain special directions within the crystal. In crystals of the tetragonal, hexagonal, and trigonal systems there is one direction, parallel with the crystallographic vertical axis, along which no double refraction takes place. This direction, which, it must be remembered, is a direction and not an axis in a particular position in the crystal, is styled the *optic axis*. Such crystals are said to be *uniaxial*. In crystals of the triclinic, monoclinic, and rhombic systems, there are two directions along which double refraction does not take place. Such crystals are styled *biaxial*, and the plane containing these two directions is the *optic axial plane*.

The directions of these optic axes may vary slightly, and sometimes considerably, for light of different colours.

In uniaxial crystals, one of the rays formed by double refraction obeys the laws of single refraction, and is styled the *ordinary ray*. The refractive index afforded by it is thus constant, and the refracted ray lies in the plane of incidence. When the incident ray is normal to the surface, the ordinary ray continues in the same direction in the crystal.

The other ray, however, which is known as the *extraordinary ray*, furnishes a refractive index that varies with the direction of propagation in the crystal, and it does not necessarily lie in the plane of incidence.

Extraordinary rays, moreover, except for certain special directions of propagation, are deflected from the normal even when the entering light is normal to the refracting surface; but they assume the normal direction on emerging at a surface parallel with that by which the light entered the crystal.

In uniaxial crystals, the extraordinary ray has the same refractive index as the ordinary ray when propagated, by refraction at an oblique face, along the direction of the vertical axis of the crystal. That is to say, the velocity of the ordinary and extraordinary rays is the same along the optic axis, and consequently there is no double refraction for this direction. When, however, the extraordinary ray is propagated in any azimuth perpendicular to the optic axis, its refractive index is at its maximum difference from that of the ordinary ray. Hence the refractive effect of a uniaxial mineral cannot be appreciated from a single index-value. The index for the ordinary ray, and also that for the extraordinary ray when at its maximum difference from the ordinary index, must be both stated, sodium light being used. They are indicated respectively by ω and ϵ. Where these indices are near one another, an average statement may be of service.

In biaxial crystals both of the rays formed by double refraction are extraordinary. There are, however, three planes in the crystal perpendicular to one another which possess the special property that one of the two rays of any pair that can be propagated in them has a constant velocity and refractive index. For these planes, then, one of the rays of a pair formed by double refraction, and lying in the plane, behaves as an ordinary ray. The refractive index of the crystal is determined in sodium light for each of these three "ordinary" rays, and all three, the maximum (represented by the symbol γ), the minimum (α), and the third (β) which is an approximate mean, must be quoted to represent fairly the refractive effect of the biaxial crystal. When a general refractive index is stated, it is the average of these three indices, $\frac{\alpha + \beta + \gamma}{3}$; but such a statement is rarely satisfactory. See p. 133.

The most important property of the rays produced by double refraction remains to be stated. Even where reflection and refraction occur at the surface of an isotropic and therefore singly refracting substance, a certain portion of the reflected rays are found to be plane-polarised. When the angle of incidence is so adjusted that it is the complement of the angle of refraction, the courses of the refracted and reflected rays are perpendicular to one another, and all the reflected light, if of one colour, becomes plane-polarised, its vibrations taking place parallel with the reflecting surface. The light that enters the isotropic substance becomes also plane-polarised, its vibrations taking place parallel with the plane of incidence. If a bundle of plane-polarised rays is incident on an isotropic substance, the refracted rays remain polarised in the same plane on entering and leaving the substance, except for the special cases in which "rotatory polarisation" takes place.

In doubly refracting media, however, when ordinary incident light is used, and in most cases when polarised light is used, two sets of rays are formed, if the direction of transmission in the crystal is not an optic axis; *each ray so produced is plane-polarised, the vibration-planes of the two sets of rays being always perpendicular to one another.*

In ordinary observations with the microscope, plates cut from crystals are employed, the two principal surfaces of these plates being parallel with one another. The light is caused to enter normally to one surface; then, in a doubly refracting crystal, the two resulting sets of rays, which will comprise either an ordinary and an extraordinary set or two extraordinary sets, emerge from the other face of the plate normally to its surface. Their vibration-planes are thus perpendicular to this face on emergence, and the traces of these planes on that surface may be called their *vibration-traces*, and indicate the actual direction of vibration in the two sets of emerging rays. These traces are perpendicular to one another, and may be represented diagrammatically as in Fig. 54.

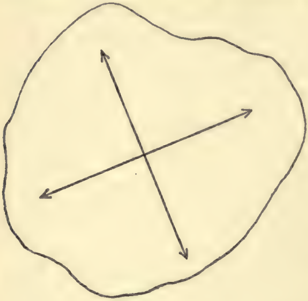

FIG. 54.

One of the two rays formed by double refraction has a less velocity than the other within the crystal. Though this difference of velocity is very small, we may speak, for convenience, of a *fast ray* and a *slow ray* in every pair produced by double refraction. In practice, since a ray enters at every point of the first surface of the crystal-plate, a fast and a slow ray emerge along the same line at every point of the second surface, though the members of each pair belong to different incident rays. The surfaces being parallel, the direction along which the rays emerge is that of the original incident rays.

In every doubly refracting crystal there is some direction of propagation within the crystal along which the slow and the fast ray move with a maximum difference of velocity, and therefore of refractive index. We then have to deal with the refractive indices of the fastest and slowest rays in the crystal. Since the indices vary according to the colour of the light, the yellow light of a sodium flame is employed in determinations.[1]

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[1] On the methods of determination, see Tutton, "Crystallography," pp. 597 and 619.

The difference of the two extreme indices obtained with sodium light measures the *strength of the double refraction* or *birefringence* for the particular mineral. In quartz the extreme indices are 1·544 and 1·553, giving a difference of 0·009; this represents a weak double refraction. In pennine, one of the chlorites, the difference is as low as 0·001. In olivine the minimum and maximum indices are 1·653 and 1·689; the difference, 0·036, indicates strong double refraction. In aragonite we reach a difference of 0·156. In calcite, with a difference of 0·172, the double refraction is exceptionally strong; hence the two rays formed have for most positions so marked a difference of direction in the crystal that two images are seen when a small spot is viewed through a crystal about a centimetre in thickness. In ordinary minerals the existence of double refraction is discoverable only by far more delicate means.

Relation between Refractive Index and Total Reflection.

Whether single or double refraction takes place within a crystal, a ray may have so great an obliquity to the inner side of the surface of emergence that it becomes totally reflected in place of passing on into the air. The ray is refracted away from the normal to this surface, and, with a sufficient internal angle of incidence, the ray may be caused to lie along the surface of emergence. All rays with a still greater angle of incidence within the crystal will become *totally reflected*, at angles which of course equal their angles of incidence. There is, then, a *critical angle* of internal incidence for the denser of any pair of media, depending on the refractive index, beyond which the light is returned into the denser medium. The result is a loss of light if the observer looks through a crystal at a light-source, since certain oblique rays may be reflected away from him, and an increase of brilliance if the light-source is behind the observer. The critical angle in the case of highly refracting substances and air is so small that a large part of the light entering the crystal from behind the observer may be returned so as to catch his eye. By suitably cutting the artificial back-planes in a gem, a still larger proportion of the entering rays may be caused to impinge obliquely on surfaces at angles greater than the critical angle, and thus to add brilliance to the gem.[1]

The possibility of total reflection has led to the construction of simple *refractometers.* Dr. G. F. H. Smith[2] has devised an instrument on the principle of the *total reflectometer*, by which the refractive indices of minerals can be read off to at least the second place of decimals, provided that they have a flat surface that can be brought into contact with that of the hemispherical lens of the refractometer (Fig. 55.) This hemispherical lens is made of a dense glass which has a refractive index for air and sodium light of 1·80. The crystal plate or face of a crystal, or of a cut gem, is laid on the flat upper face of the lens. To avoid the inclusion of an air-film, a drop of methylene iodide, which has a refractive index of 1·75 when pure, or 1·80 when saturated with sulphur, is pressed between the object and the lens, and the total reflection takes place at the

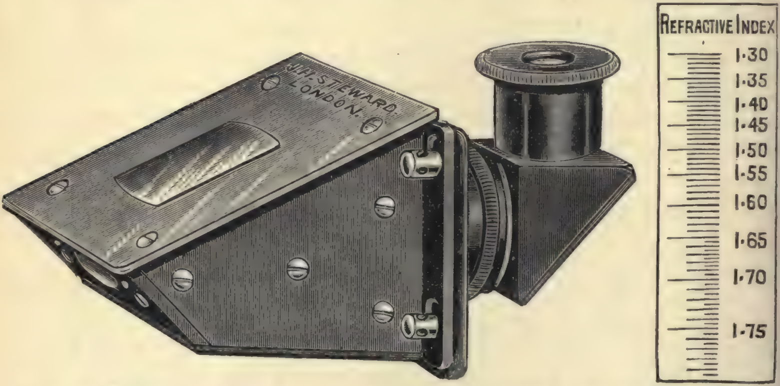

FIG. 55.—Herbert Smith's refractometer, with scale. As seen after reflection, the upper part of the scale represents the lower part as it stands in the instrument.

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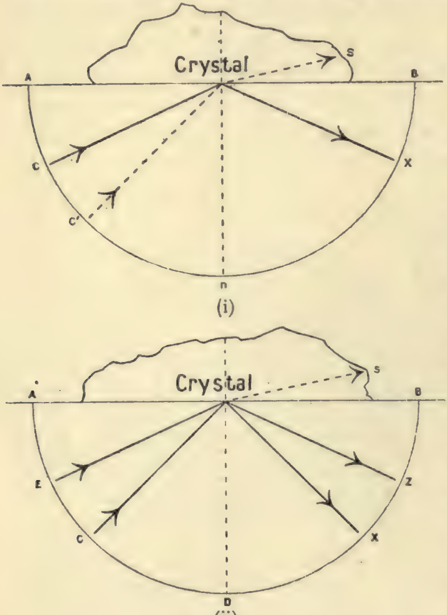
[1] See W. McLintock, "Guide to the Collection of Gemstones in the Museum of Practical Geology," London (1912), 10.

[2] *Min. Mag.*, **14** (1905), 83, and *ibid.* (1907), 354. Made by J. H. Steward, Ltd., 457, West Strand, London.

upper surface of this film. The object, therefore, must not have a higher refractive index than that of the liquid used. The brittle and soft nature of the highly refracting glass must be borne in mind when the object is being adjusted on it. Ordinary diffused light-rays enter from one side of the hemisphere, and a small part is reflected out to the other side when refraction takes place at the surface of the crystal. Those rays, however, that are sufficiently oblique are *totally reflected* from the plane surface of junction with the object. These rays find a focal surface on the other side of the hemisphere, this surface being part of a sphere concentric with the hemisphere of the lens. Dr. Smith's instrument receives the emerging rays on a lens which corrects the curvature of this focal surface, and the observer views them with an eye-piece as they pass through a transparent graduated scale, on which the indices of refraction are read off directly.

Let us first take the case where an object is singly refracting (Fig. 56, i). Rays of various obliquities, as C′S, enter the object; but those beyond the obliquity of the ray C, which has the limiting angle of incidence, are totally reflected. Rays entering the hemisphere in the region AC are therefore received on the opposite side in the region BX, which appears brighter than the region XD. The limit of these two regions is seen as a line between a bright and a dark grey area on the transparent scale-plate, and its position varies with the refractive index of the object. Owing to the difference of refractive index for light of different colours, sodium light is used, and may be readily obtained from a bead of common salt held on a platinum wire in the flame of a spirit lamp or a Bunsen burner. If white light is used, the position of the yellow band in the resulting coloured fringe can be read off.

If the object is doubly refracting (Fig. 56, ii), we must remember that there will be a series of slow rays and one of fast rays formed in it. The fast rays will receive a greater increase of velocity than the slow rays, in comparison with the velocity of the ray in the hemispherical lens, and in consequence the fast series of rays will deviate more from the normal than the slow series. The fast rays resulting from certain critical oblique incident rays will therefore suffer total reflection as CX, while the corresponding slow rays CS will enter the crystal. For a certain greater obliquity in the incident rays, the light will not enter the crystal at all. This occurs when the critical angle for the slow rays has been also passed. Two regions of greater brightness will thus be marked off from the general dark greyish one on the scale of the refractometer. In one, BZ, the brightness will be considerable, since all the rays from the region AE of the lens are totally reflected. In the other, ZX, the brightness will be less, since it receives by total reflection only a part of the light that enters the lens between C and E. The edges of the regions BX and BZ on the scale give therefore a measure of the refractive indices of the mineral for the fast and slow rays respectively in the particular position adopted for the crystal plate. If this plate is rotated on the plane surface of the hemispherical lens, the positions of one or of both of the boundaries may be seen to change, and one edge may even move across the other. In all cases, the extreme positions give the least and greatest of the refractive indices of the crystal (pp. 95 and 133). Of the intermediate positions, the lower maximum gives the mean refractive index, and the higher minimum depends on the direction of the plate in regard to the optical symmetry of



(i)

(ii)

Fig. 56.

the crystal. In most cases, the two edges are close together in the field.

Further Applications of Total Reflection.

The fact that reflections take place from the surfaces of transparent bodies surrounded by media having a different density enables them to be seen in the air, and their forms to be appreciated. When immersed in air, moreover, total reflection may take place from the back planes and surfaces of transparent crystals, and this renders them yet more distinct from their surroundings. In order to check reflections from the irregular surfaces of mineral grains, or from the little pits and hollows that exist on the most accurately ground surfaces of preparations for the microscope, the objects are commonly immersed in Canada balsam, which has a refractive index of about 1·547. This renders minerals with about this index more transparent than others that have a higher or a lower index. Those with a higher or a lower index reveal the pittings and irregularities of their surfaces under the microscope, and are said to exhibit *relief*. In the case where the index of the mineral is higher than that of the balsam, a certain amount of total reflection takes place in the preparation, as light transmitted from below through the mineral reaches its upper surface, and is about to enter the less refracting Canada balsam. When the index of the mineral, as in fluorspar, is lower than that of the balsam, total reflection may occur at the oblique surfaces of pittings on the under side of the preparation. In either case, some light is thrown back that would otherwise have passed through the crystal-slice, and the visibility of irregularities on the ground surface is increased.

We can thus easily pick out in a rock-section containing various minerals those that have refractive indices near to that of the surrounding balsam. These appear clear and unpitted, and thus more transparent. In doubly refracting crystals where there is a marked difference between the indices for rays travelling in different directions in the crystal, the pitted effect may be more noticeable in some sections than in others.

Where bodies of widely different refractive indices lie in contact in a rock-section, dark and strong boundaries occur between them. By using oblique illumination, which is obtained by holding the finger under the object so as to cut off normal rays rising from the reflecting mirror, bright edges due to total reflection often become apparent. This method, aided by a condenser which is capable of being raised or lowered between the finger and the object, brings out differences of refractive index very effectively.[1]

F. Becke[2] has pointed out that the totally reflected light from the surface of junction of a mineral and Canada balsam, or of two adjacent minerals of different refractive indices, if this surface is perpendicular to those of the preparation, may produce a brighter band along the boundary. The additional light that produces the bright effect is thrown up on the side on which the substance of higher refractive index lies, and can be seen when the microscope-tube is slightly raised after focusing on the boundary in the section. When, on the other hand, the tube is slightly lowered, so that the microscope is focused on a plane somewhat below that of the section, the bright band is seen to lie on the side of the substance of lower refractive index.

G. W. Grabham[3] discusses this reaction on the basis of an explanation given to him by E. M. Anderson, and shows how the occurrence of junctions oblique to the surfaces of the microscopic section must be taken into consideration. If the surface of junction of two substances is so inclined that the substance of higher refractive index (H) overlaps that of lower index (L), rays coming up from below through L against the junction are deviated towards the normal to the junction and are thus bent towards the side on which H lies. It may be remarked that on emergence into the air above the section they are still more deviated to this side. If L overlaps H, total reflection is possible from the surface of junction, the rays so reflected being directed towards the side on which H lies. If L similarly overlaps H, but the surface is so oblique to the surfaces of the microscopic section that no totally reflected rays reach the objective of the microscope, there is none the less an accumulation of light on the side on which H lies, owing to the bending to that side of rays which pass through the inclined junction, since such rays are then bent away from the normal to the junction on entering L.

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[1] See F. E. Wright, "Oblique illumination in petrographic microscopic work," *Amer. Jour. Science*, **35** (1913), p. 67.

[2] "Ueber die Bestimmbarkeit der Gesteinsgemengtheile auf Grund ihres Lichtbrechungsvermögens," Sitzungsber. k. Akad. d. Wissenschaften, Vienna, **102** (1893), 358. For explanatory diagram, see Iddings, "Rock Minerals," ed. 2 (1911), 115. For Maschke's observations in 1872, see Wright, "Methods of Petrographic Research" (1911), 92.

[3] "An improved form of petrological microscope; with some general notes on the illumination of microscopic objects," *Min. Mag.*, **15** (1910), 341.

It is obvious that the matter is complex if we are dealing with two doubly refracting substances; but the difference between the refractive indices for the two rays concerned in any one section of a mineral is not likely to be sufficient to vitiate the general result.

Much, however, depends on the direction in which the section traverses the minerals concerned. Thus two adjacent doubly refracting minerals may possess, as a whole, different *average* refractive indices, and yet the one that has the higher average may show a lower result than that of its neighbour for the particular sections that are in juxtaposition.

A useful mnemonic is suggested by the fact that, in the observation of Becke's very useful reaction, when the tube of the microscope is *lowered*, the bright band lies in the substance of *lower* refractive index. A wide-angle objective should be used, say a quarter-inch, since oblique rays are thus brought from the object to the eye that might otherwise not reach the observer.

Schroeder van der Kolk [1] uses a number of highly refracting liquids of known refractive power to determine the refractive indices of small grains. In monochromatic light, oblique rays striking the crystal-surface cause no bright-line effect if the grain has the same index as the liquid in which it is immersed.

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[1] "Tabellen zur mikroskopischen Bestimmung der Mineralien nach ihrem Brechungsindex" (1906).

The use of the coloured marginal fringes that appear when white light is employed is discussed by F. E. Wright (*Amer. Journ. Science*, **35**, 1913, p. 71).

The Employment of Polarised Light in Optical Experiments.

Plane-polarised light may be obtained by reflection. A simple and reflective *polariscope* can be made as follows. A glass plate backed by dull black paper is stuck down in a horizontal position on a wooden stand. A tube of tin or card is set up inclined to the horizontal at the most effective angle, about $35\frac{1}{2}°$, for receiving the polarised rays reflected from the plate. At the upper end of the tube a second and similar reflecting plate is fixed, so that the axis of the tube is inclined to it also at $35\frac{1}{2}°$, but so that it can be rotated about this axis. One method is shown in Fig. 57; another is to attach it rigidly at the proper angle to a perforated cap which fits over the end

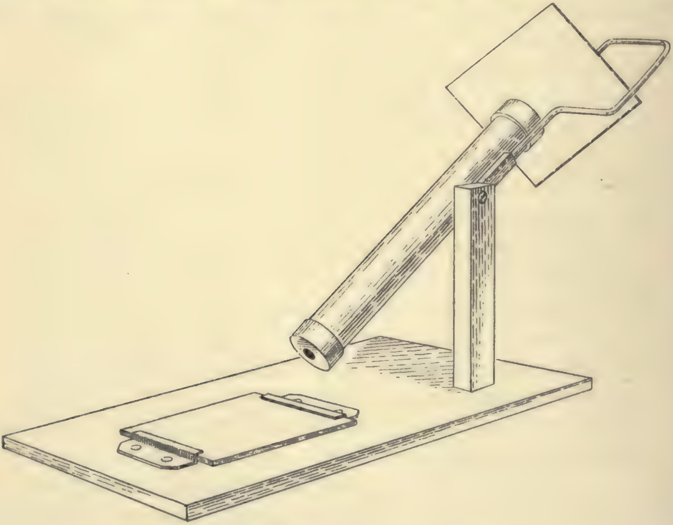

FIG. 57.—Simple reflecting polariscope.

of the tube. The plate can then be rotated, while the angular relation between it and the axis of the tube remains unchanged. Light sent up the tube from the horizontal mirror can be seen by the eye as it looks into the upper mirror. If the latter is placed with its plane at $35\frac{1}{2}°$ to the horizontal plane, the polarised reflected rays from the lower mirror, which vibrate parallel with the surface of that mirror, are received by the upper mirror in the most favourable position and are reflected to the eye. But when the upper mirror is rotated, so that its plane is vertical, these rays cannot be reflected from it. They are absorbed, and darkness results. We have here the two essential parts of a polariscope, a *polariser* below and an *analyser* above. The darkness arrived at, however, is only partial, owing to the reflection of diffused rays besides those polarised by the lower mirror. A second perforated cap may be placed on the lower end of the tube, and mineral plates laid inside it will show the characteristic phenomena of interference-colours, extinction, etc., that will be described later in connexion with the examination of crystals by means of polarised light.

The polariser and analyser used in the most effective instruments are elongated cleavage-rhombohedra of transparent calcite ("Iceland spar"), converted into *Nicol's prisms*, and familiarly known as *nicols*. The construction of these prisms is well known from descriptions in Tyndall's "Lectures on Light" or in any ordinary physical text-book. It is obvious that we can obtain plane-polarised light for experimental purposes if we can isolate one of the two sets of rays that emerge from the surface of a transparent doubly refracting crystal. William Nicol of Edinburgh, a retired teacher of Natural Philosophy, effected this in 1828[1] by selecting a calcite cleavage-form of such a length that, when cut across from B to C (Fig. 58), the plane of section is nearly perpendicular to the end planes AB and CD. These end planes are usually ground down so that the angles BAC and BDC are 68° in place of the 71° of the natural form. The cleavage-form is then cut through diagonally from B to C, and the two halves are stuck together again with Canada balsam, which is isotropic and has a refractive index for any ray of about 1·547. Ordinary light is directed into the Nicol's prism parallel with its longer edges. Since calcite is uniaxial, a set of ordinary and a set of extraordinary rays are formed. The cross-section of the prismatic form is a rhombus, and the ordinary rays vibrate parallel with its longer diagonal, while the extraordinary rays vibrate parallel with its shorter diagonal. In calcite, the ordinary ray is more refracted than the extraordinary. For extraordinary rays in the direction of propagation selected, the calcite has a refractive index of 1·536. These rays deviate only slightly from parallelism with the long edges of the nicol, are scarcely affected by meeting the film of Canada balsam, which has a closely similar index, and are finally transmitted into the air along a path parallel with that by which they entered the prism. The ordinary rays, however, for which the calcite has a constant refractive index of 1·658, are transmitted more obliquely, and encounter a substance of much lower index in the balsam film. With the dimensions selected for the nicol, they are totally reflected at the surface of the film and are thrown out against the dull black casing in which the nicol is embedded for experimental use. Hence very little return of light by reflection is possible, and practically only the extraordinary rays reach the eye. We thus obtain plane-polarised light vibrating in one plane only, and we know that its vibration-plane is parallel with the plane uniting the obtuse angles of the rhombus-section of the nicol, that is, with the shorter diagonal of the nicol.[1]

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[1] The first explanation of the action of the Nicol's prism appears to have been due to E. Sang in 1837. His paper, with a note by Tait, was not published until 1861 (*Proc. Roy. Soc. Edinburgh*, **18**, 323).

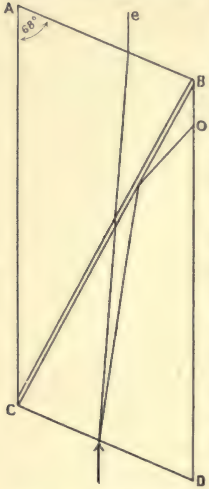

FIG. 58.—Section of a Nicol's prism.

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[1] As J. P. Iddings points out ("Rock Minerals," 2nd ed., 1911, p. 136), forms of nicol are made in which the upper and lower faces are

Two Nicol's prisms mounted so that one at least can be rotated about its long axis, and so that an object can be examined between them, constitute the polariscope that is now ordinarily used. If the lower nicol, or *polariser*, is rotated, the vibration-plane of the emerging rays, which may be described as the vibration-plane of the nicol, can be brought perpendicular to that of the upper nicol, or *analyser*. The unaided eye does not distinguish polarised light; but the analyser at once detects it when the two nicols are in their *crossed position*. Darkness then results, since the rays transmitted by the polariser are vibrating in the position for ordinary rays in the upper nicol. Consequently, they here proceed as ordinary rays without double refraction, and are all totally reflected at the balsam film. In intermediate positions during rotation, light will be transmitted, since the rays from the polariser are then doubly refracted by the analyser, one set passing on as extraordinary rays and thus reaching the eye. When the nicols have their vibration-planes parallel, as much light as possible is transmitted, since the rays from the polariser all remain as extraordinary rays in the analyser.

The amount of light transmitted for any given position of the lower nicol during rotation is determined on the principle of the parallelogram of forces. The vibration of the ray from the polariser has a certain amplitude. This is resolved along two vibration-directions in the lower half of the analyser. If both the rays due to double refraction could emerge, the amplitudes of their respective vibrations would be geometrically represented as BC and DE in Fig. 59, where PO is the vibration-plane of the polariser, XZ is the amplitude of the ray emerging from it, and AN and *an* are the vibration-planes of the calcite forming the analyser. Both these planes are effective in the lower half of the analyser: but the rays vibrating parallel with AN alone come through to the eye. The light that

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perpendicular to the longer edges of the cleavage-form, which allows of the direct transmission of the ordinary rays without refraction and of the total reflection of the extraordinary rays; if, then, such a nicol is used, it must be remembered that the vibration-plane of the emerging rays is parallel with its longer and not its shorter diameter.

passes through is in this case fairly strong, having the amplitude ED due to resolution along AN.

It is clear that darkness occurs twice during a rotation of the polariser.

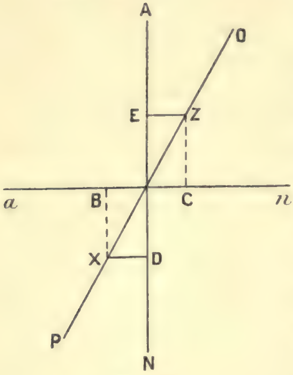

FIG. 59.

In practice, the polariser is fixed in a cylinder of cork, and this is mounted in a brass tube. This is again set within a tube which bears an index-pointer, and a graduated circle moving with the polariser shows its position in regard to the analyser, which remains fixed. A spring-catch is usefully added, to indicate when the crossed position is reached. These indicators must be checked from time to time, since the nicol in its cylinder of cork may shift round within its tube.

The observation of axis-pleochroism (see p. 111) is made with the polariser only. All other observations are made with the two nicols, and these are almost always required to be in the crossed position. But it is necessary to bring their crossed vibration-planes into varying positions in regard to those of the crystal that is placed between them. This is usually done by fitting a polarising microscope with an accurately centred rotating stage, graduated in degrees upon its margin. The difficulty of exact centring for high powers led Allan Dick to introduce the well-known Dick-Swift instrument, in which the nicols are both rotated in the crossed position, by means of cog-wheels and a connecting-rod, while the object remains fixed. This accurate method is applied to petrological microscopes by Swift & Son of London and has been imitated by some continental firms. The latest form of the Dick-Swift instrument is due to and is described by G. W. Grabham[1] (Fig. 60). It should be compared with an equally modern

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[1] "An improved form of petrological microscope," *Min. Mag.*, **15** (1910), 335.

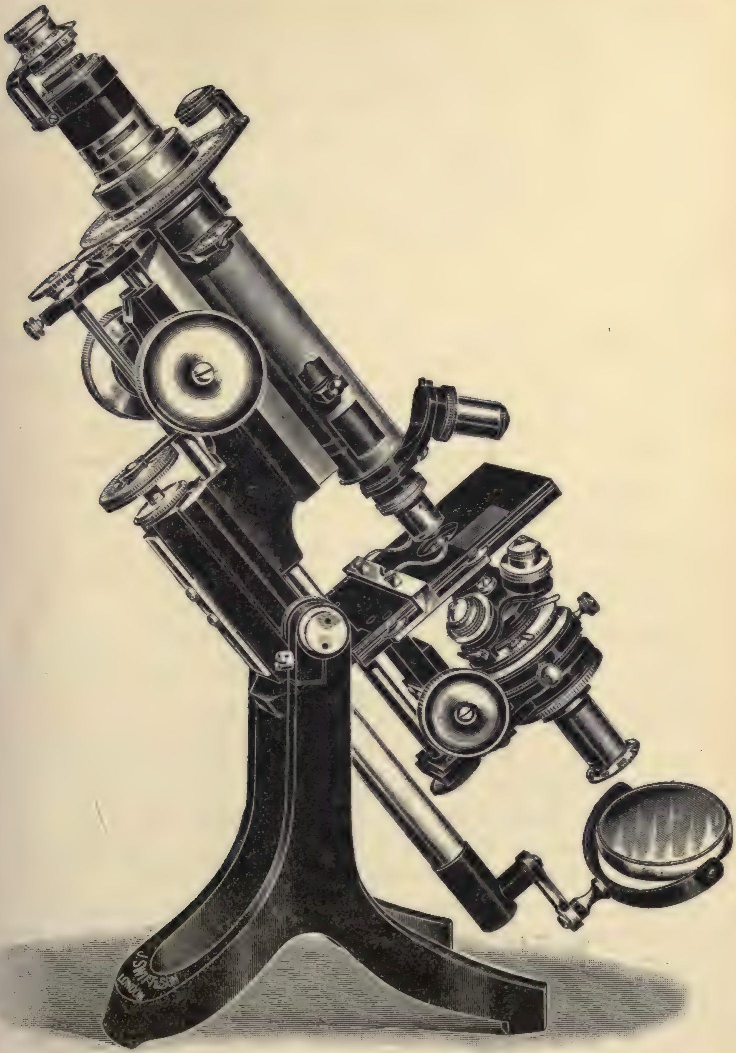

FIG. 60.—Petrological microscope, with fixed stage and rotating nicols (Dick-Swift pattern, as modified by Grabham).

instrument devised by F. E. Wright,[1] in which the nicols are simultaneously revolved by mounting them in circles connected by projecting rods with a rigid bar. The small errors due to the possible wear of cog-wheels are thus eliminated. The firm of Fuess makes a simple instrument embodying Wright's principle.

In all such microscopes, it is important that both analyser and polariser can be quickly and independently thrown out of operation.

Pleochroism.

The colour of minerals is so striking a character that is has been dealt with in Chapter II, in advance of the present optical considerations. The colour of the light transmitted by a crystal depends on its differential absorptive effect on the mixed rays of white light. Rays of some colours may be greatly reduced in amplitude, while those of other colours are more easily sent through. Isotropic substances show the same colour for the same thicknesses of plates cut from them, whatever the direction in which the plate has been cut, provided that the colouring matter is evenly diffused. A sphere cut from a crystal of the cubic system will thus show the same tint, in whatever direction it is viewed. But doubly refracting crystals are often seen to be *pleochroic*, and probably are pleochroic in all cases, although the eye may appreciate the fact only in the more striking instances. *Pleochroism* implies that the colour of the transmitted light is not the same for equal thicknesses of the crystal in all directions.

A sphere cut from a uniaxial crystal shows two extreme colours according to the direction of the light passing through it, and these directions are perpendicular to one another. One is found to be the direction of the optic axis, and the other is any direction perpendicular to that axis. Hence, a cylinder cut from a uniaxial mineral with its axis parallel to the optic axis may be rotated about that axis without showing change of tint; but a section perpendicular to the optic axis and of a thickness equal to the diameter of the cylinder will show a different tint. Sometimes the difference is so marked that the thicker of two sections cut in different directions from a mineral will transmit much more light than the thinner one.

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[1] "A new petrographic microscope," *Amer. Journ. Sci.*, **29** (1910), 407.

A sphere cut from a biaxial crystal will be found to show two extreme tints when the source of light is viewed through it in two directions perpendicular to one another, and these directions will be found to lie in the optic axial plane and to bisect the angles between the optic axes. A third and approximately mean tint, however, is seen when the light is transmitted perpendicular to the optic axial plane. Hence, a cylinder cut with its axis lying in any direction will show a change of tint as it is rotated about that axis.

The result is that pleochroic minerals may appear of very different colours in a rock-section, according to the direction in which their crystals have been traversed by the section. Biotite mica may appear deep brown and pale straw-yellow in the same rock-section. Amphiboles are much lighter in colour when viewed down the vertical axis than they are when cut parallel with it. This phenomenon, by which sections cut parallel with different faces of a crystal appear of different *face-colours* for transmitted light, is known as *face-pleochroism*.

If the plate examined is doubly refracting, the colour seen is due to the two sets of polarised emerging rays. The absorptive effect of the crystal is not likely to be the same for both these sets of rays, vibrating as they do in planes perpendicular to one another. If the plate is rotated above a polariser, the analyser of the instrument being removed, a change of tint is seen, two extreme tints occurring in positions 90° apart. The face-colour has, in fact, been divided into two *axis-colours*. An axis-colour, of course, reveals itself whenever the vibration-planes of the crystal-plate are parallel with those of the calcite that forms the polariser. The emerging rays from the polariser are then vibrating in one of the vibration-planes of the crystal-plate, and are in consequence not doubly refracted. The rays emerging from the crystal-plate thus show the colour imparted by the crystal to rays vibrating in one direction only, the complementary effect being seen when the other vibration-trace is brought parallel with that of the rays transmitted by the polariser.

This method of observing the axis-colours successively by bringing different directions of the crystal parallel with "the plan of primitive polarisation," of a polariser is due to Brewster in 1819. Haidinger, in 1844, introduced the *dichroscope*, by which the two colours are seen simultaneously. The more elaborate instrument sold by opticians does not need description here, since the simple form first used by the inventor displays the phenomena excellently. An elongated transparent cleavage-form of calcite, such as can be bought for a small sum, displays two separate images of a sufficiently small object, when this is viewed through the length of the cleavage-form. A square hole in a card can be cut of such a size that the two images of it lie exactly side by side when seen through the particular piece of calcite used. When, by rotating the calcite, these images appear with two of their sides coincident, the coincident sides are parallel with one of the vibration-planes of the calcite. The calcite and the card may be mounted in a card tube in these relative positions. If a translucent and coloured mineral is held behind the aperture in the card in a position in which it is doubly refractive for the transmitted rays, and the tube containing the calcite and perforated card is rotated, the images of the square hole will have the same colour when the vibration-traces of the mineral bisect the angles between those of the calcite. A rotation of the tube through 45° will bring these traces into parallelism, and the two images will show the extreme differences of tint for the particular face-colour examined, since one of them is then formed entirely of rays vibrating in one of the critical directions in the crystal, and the other is formed of rays vibrating in the other critical direction. The difference of tint may be much greater for some face-colours than for others, and in some cases may be barely appreciable. Coloured isotropic bodies will of course show no change during the rotation of the calcite, and the section of a uniaxial mineral, such as tourmaline, perpendicular to the optic axis is thus distinguished from one parallel to the axis.[1]

For the description of pleochroism in uniaxial minerals, the two extremes are selected in sections parallel to the optic axis, all such sections being equivalent. One of these extreme axis-colours is found to occur when the rays vibrate parallel with the axis, and the other when they vibrate perpendicular to it. We shall see later that these two tints are due respectively to extraordinary and ordinary rays traversing the crystal perpendicular to the optic axis (p. 126).

In biaxial minerals, three directions of vibration are selected. The two extreme axis-colours for the whole crystal are found in the section parallel with the optic axial plane, when the rays travel in the crystal perpendicular to the surfaces of the section. They are the colours imparted to rays vibrating respectively parallel with the two directions that bisect the angles between the optic axes. One of these vibration-directions is that of the fastest rays in the crystal, and the other that of the slowest rays. These directions are commonly indicated by the Gothic letters 𝔞 and 𝔠 respectively (X and Z of Iddings, and n_p and n_g of Michel Lévy).[2] The third and intermediate axis-colour recorded is that shown by rays vibrating parallel with the direction perpendicular to the optic axial plane, that is, perpendicular to both of the directions yielding the extreme tints. This direction is known as 𝔟, or Y, or n_m. The tint corresponding with it will be one of the axis-colours found in any section perpendicular to the optic axial plane; but the other axis-colour of such a section may be either of the extreme tints or something intermediate, according to the orientation of the section in the crystal. See Fig. 61.

As an example, we may take the description by Rosenbusch ("Hülfstabellen zur mikroskopischen Mineralbestimmung,"

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[1] C. Leiss has applied the dichroscope to the petrological microscope, using a narrow oblong opening (*Neues Jahrb. für Min.*, 1897, **2**, 92).

[2] On the use of these letters see F. E. Wright, *Amer. Journ. Sci.*, **35** (1913), 133.

1888) of the pleochroism of hypersthene :—"𝔠 green, 𝔞 brown-red, 𝔟 reddish yellow." Or of actinolite :—"weak, in green tints, $\mathfrak{c} > \mathfrak{b} > \mathfrak{a}$," which means that the deepest tint due to absorption is found when the vibrations of the light take place parallel with 𝔠. From another column of the tables, we find that 𝔠 in actinolite is the direction bisecting the obtuse angle between the optic axes.

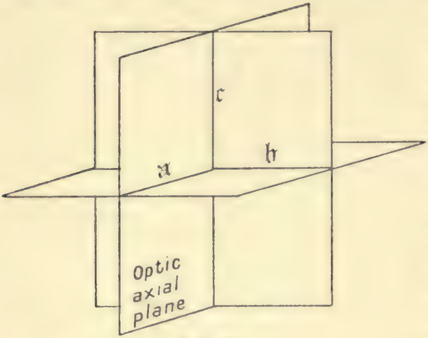

FIG. 61.

In Lévy and Lacroix, again ("Tableaux des Minéraux des Roches," 1889), we find the pleochroism of andalusite described as "n_g pale olive, n_m olive-green, n_p flesh-pink." Here n_g (or 𝔠) has the same relation to the optic axes as in actinolite.

An extreme case of difference of absorption for rays vibrating in different directions is seen in vertical sections of the trigonal mineral tourmaline. The extraordinary rays, which possess in this case the greatest velocity, come through, vibrating, as in all uniaxial minerals, parallel with the optic axis. The tint is usually green or brown. The ordinary rays, which are the slowest and vibrate perpendicular to the optic axis, suffer so great a reduction in amplitude that a thickness of 3 or 4 mm. of the mineral suffices to cut them off from the eye. A fairly thick slice of tourmaline, cut parallel with the optic axis, transmits, then, only extraordinary rays, and two such slices, laid over one another, can be used as a polariscope. When their optic axes are parallel, light is transmitted; when they are crossed at right angles, the field is dark. Circular plates thus cut are mounted in brass rings in a handle resembling that of a pair of tongs, so that one plate can be revolved, and the pair forms the *tourmaline pincette* used by jewellers for the detection of glass imitations of gems. Many interesting experiments on minerals can be carried out between the plates of such a simple polariscope.

Examination of Crystal-Plates between Crossed Nicols.

Though many of the observations about to be described can be carried out on uncut crystals, or on naturally or artificially powdered material, it is always convenient if a section can be studied, even if we do not know how it is oriented in regard to the crystal of which it forms a part. As previously remarked, the two surfaces of the section should be parallel, and the light should be thrown up normally to the lower surface. It then emerges normally at the upper surface, in spite of any refraction that may take place in the case of extraordinary rays. The vibration-directions of the emerging rays are then parallel with the surface of the section.

A mineral of the cubic system, whatever its class, is isotropic in all sections, and thus produces no effect on the dark field when viewed between crossed nicols. Rotatory polarisation (p. 127) is known in some few cubic substances, as also in some liquids; but in a work on minerals the phenomenon need only be dealt with in the case of uniaxial crystals.

Doubly refracting plates, however, in most positions must produce a rotation of the vibration-plane of the rays reaching them from the polariser, and must in consequence destroy the dark field due to the crossed nicols, just as would be the case if we rotated the polariser from the crossed position. We have, however, to consider two sets of emerging rays, with vibration-planes perpendicular to one another. In Fig. 62, the ray emerging from the polariser with amplitude AB is resolved by the crystal along its vibration-directions as two rays with amplitudes CD and EF.

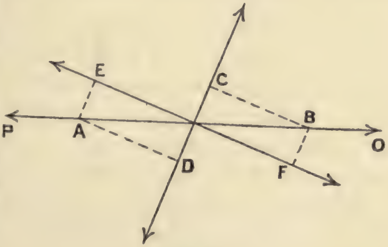

FIG. 62.

If the two vibration-planes of the crystal-plate are parallel with those of the polariser, the rays from the polariser are not doubly refracted, since their vibrations are already taking place in one or other of the planes into which the structure of the crystal would bring them. Hence the dark field between crossed nicols remains unaltered. If the crystal-plate is rotated, or if the crossed nicols are rotated about the plate, darkness occurs four times in a rotation. When the plate has no effect on the vibration-plane of the polarised light, it is said to be in a *position of extinction.*[1] The eye can judge the position of extinction, or maximum darkness, within about 1°, and it is well to make repeated experiments, measuring the rotation by the graduations on the stage of the microscope or other instrument. It will soon be clear that extinction occurs in four azimuths 90° apart. Between these positions, light is seen, attaining its maximum when the vibration-traces of the plate are at 45° with those of the nicols. This light is often of a particular colour, shading down towards darkness, through reduction of its amplitude, but not altering its period, as extinction is approached.

Since the positions of extinction indicate the positions of the vibration-traces, they are of great importance in determinative work, wherever some indication is to hand as to the orientation of the section. Sections parallel with the maximum elongation of a crystal, which is usually the axis of the vertical prismatic zone, are very useful in this matter, and the prisms that may be found in fragmental rocks, such as sands or volcanic ashes, or that may be obtained on powdering a rock, are desirable objects for extinction-tests. We know how the vibration-directions lie in a large number of minerals in regard to the *c*-axis, and, if this axis is set parallel with one of the cross-wires in the eyepiece of the instrument, we may see whether the mineral prism is in a position of extinction, or whether rotation is required to produce darkness. Here the guide-line is the *c*-axis, and the amount of rotation required away from any such selected guide-line is styled the *angle of extinction*.

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[1] In some few minerals, the positions of the vibration-planes for light of different colours differ so widely that extinction can only be obtained when monochromatic light is used.

The traces of vertical or other known cleavage-planes serve as useful guide-lines, allowing tests to be applied to sections of irregular outline. In the series of sections that include the guide-line, there will be one so oriented as to give a maximum extinction angle; but the measurement of such angles in a number of haphazard sections will give a good idea of the character of the mineral.

Where the section is dark when the guide-line is vertical or horizontal in the field of the microscope, it is said to show *straight extinction*.

Various devices have been introduced to render the observation of the position of extinction more precise. A plate of gypsum (selenite) giving a particular violet tint between crossed nicols when its vibration-traces are at 45° with those of the nicols is mounted in a brass frame so that it is in this position when slid into a slot between the objective of the microscope and the analyser. The eye is especially sensitive to the tint selected, and this tint is, of course, seen when the object lying below it has no effect on the vibration-plane of the rays from the polariser. A doubly refracting crystal-plate with its vibration-traces parallel with those of the nicols fulfils this condition. Any rotation of the object from this position alters the colour of the gypsum plate. The position of the vibration-traces in the object can be determined in this way with somewhat greater accuracy than by the estimation of the position of greatest darkness between crossed nicols. The observation is greatly assisted if an edge of the object can be brought into the field beyond which the isotropic glass slip and the balsam used for mounting can be seen. In the isotropic area the characteristic tint due to the gypsum is seen throughout a rotation of the object, and any deviation from it due to the object can at once be recognised.[1]

We have noticed that in carrying out experiments on extinction (p. 116), when white light is used, the light seen in intermediate positions of a rotation is usually of a particular colour. Were we to examine this colour with a spectroscope, it would be found not to be pure, but to result from a combination of rays from various portions of the solar spectrum. These *interference-colours* deserve particular attention.

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[1] For other methods, see J. P. Iddings, "Rock Minerals" (1911), 150; and F. E. Wright, *Amer. Journ. Science*, **26** (1908), 349.

The light that reaches the eye in observations between crossed nicols is not entirely the same as that which emerges from the crystal-plate. We receive only that portion of the rays which is resolved along the direction of transmission of the upper nicol. We are dealing, moreover, with the resultant of parts of the two sets of rays that emerge from the doubly refracting substance. In Fig. 63, we may suppose that CD and EF represent the amplitudes of the two rays that result from the resolution by the crystal along its vibration-traces of an original polarised ray from the lower nicol (see also Fig. 62). On entering the analyser, each of these rays is resolved into two, vibrating respectively in the planes AN and *an*. The components along *an* may be neglected, since these are in the direction for rejection by the upper nicol. We receive, however, from this nicol the result of the two components vibrating along AN. Since these vibrate parallel with one another and are from the same source of light, they can interfere (p. 92).

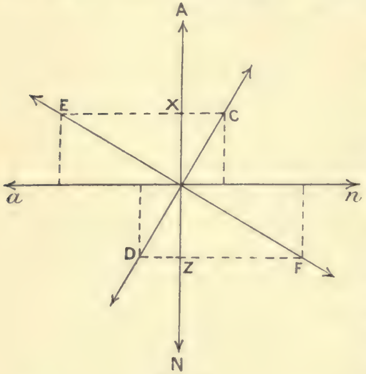

FIG. 63.

If we use white light, we may presume for ordinary minerals that the vibration-traces are practically the same for light of various colours; but the degree of interference, helpful or the reverse, will not be the same for the rays of all colours. The nature of the interference will depend upon the phases in which the rays emerge respectively from the surface of the crystal, and these will depend on the wave-length of the light, the direction of propagation (which affects its velocity), and the length of the path followed. It is clear, therefore, that in any particular case light of some colour may emerge in opposite phases in the two sets of rays produced, while light of some other colour may emerge in the same phase in both sets.

If the thickness of the crystal-plate is very small, emergence in opposite phases can only be attained by rays of short wave-length. In the case of those of longer wave-length, the difference of velocity and length of path is not sufficient to cause one of the rays that are produced by double refraction to lag behind the other by even a half wave-length. With a thicker plate, however, rays of short wave-length may emerge in the slow series with a retardation of three, or five, or seven half wave-lengths behind the rays of the same wave-length in the fast series. There may be a number of rays from different parts of the solar spectrum which emerge thus in opposite phases in the two sets into which they have been resolved.

Similarly, rays of other colours in the slow series emerge with retardations of even numbers of half wave-lengths, that is, one or two or three or four whole wave-lengths, behind their fellows in the fast series. Such rays are in the same phase in both series on emergence.

The pairs of rays of the same wave-length in the two emerging series are so far incapable of interfering with one another, since they vibrate in one set in planes at right angles to those in which they vibrate in the other set of rays.

We have now to consider the presence of the upper nicol, which is crossed in regard to the polariser. The light that reaches the eye through this analyser has been resolved, as above stated, along the plane AN. Two rays of the same wave-length emerging in the same phase may be diagrammatically represented in Fig. 64, where only half the swing of each along the respective vibration-traces is indicated. The light from the polariser vibrates along PO. The emerging rays are in the same phase, because, as indicated by the arrow-heads, a particle concerned in the propagation of each has reached the end of its swing at the same instant on the side which would allow them to be recompounded along the original direction of swing PO. The portions of these two vibrations that can be resolved along AN are seen to be equal in magnitude and opposite in direction. Light of any colour, then, emerging with its two vibrations in the same phase suffers destructive interference on the resolution of its vibrations along a direction in the vibration-plane or plane of transmission in the upper nicol.

In Fig. 65, the emerging rays of the same wave-length, derived from an original ray with its vibrations along the direction PO, are shown by the arrow-heads to be in opposite phases. On resolution along AN, the vibrations interfere helpfully, and light of any colour emerging from the crystal-plate with its two vibrations in opposite phases is thus transmitted by the analyser. The amplitude of the resulting light is double that which would have been yielded by either of its components alone.

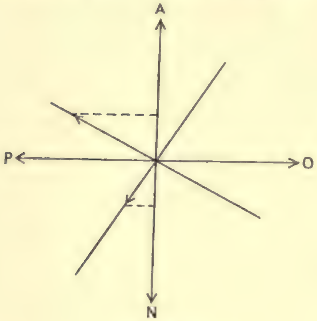

FIG. 64.

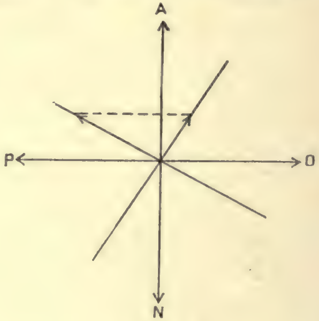

FIG. 65.

It must always be remembered that these results are obtained with the nicols in the crossed position, and that the resolution of the vibrations along the two vibration-planes of the doubly refracting prism used as an analyser leads to the apparent paradox that rays emerging from the crystal-plate in the same phase annihilate one another.

The nature of the light that finally reaches the eye is now easily realised. With a very thin crystal-plate, almost all the rays of various colours emerge with such minute differences of retardation in the two series that they remain practically in the same phase, and the field of vision is almost dark. With a greater thickness, certain rays emerge in opposite phases in the two series, and, through their helpful interference in the analyser, light comes through to the eye. The light seen is coloured, because a large part of the colours that combine to form ordinary white light is absent from it. Rays of other colours, not precisely in the same phase on emergence from the plate, are, moreover, so nearly in the same phase as to come to the eye with a greatly reduced amplitude.

Certain colours, then, predominate. Even when the plate is a thin one, certain blue, green, and yellow rays combine to produce a white effect. When a retardation of ·0003 mm. is produced in the slow rays behind the fast rays, a clear yellow predominates, since this retardation is equal to half a wavelength of a prominent yellow band in the solar spectrum. The white effect produced by rays of other colours coming through the nicol simultaneously merely dilutes this yellow. In thicker sections the colours are more mixed. Passing through oriental purple and orange, we reach faint pinks and greens, and finally a white, arising from the combination of rays from very many parts of the spectrum.

All this is best seen in a wedge cut from a doubly refracting crystal, such as a wedge of quartz with its length parallel to the optic axis of the mineral. With care, wedges of the soft mineral gypsum can be cut out with a penknife. An oblong piece of muscovite mica (a distinctly biaxial species) may be cut down in a series of steps, each of the rectangular areas thus produced showing a colour between crossed nicols appropriate to its special thickness.

When small crystals are examined between crossed nicols and have planes that slope towards one another, the thickness traversed by the light-rays varies in different parts, and the colours seen similarly vary; coloured fringes thus arise towards the thinner parts of domes or pyramids. Mineral grains, for the same reason, become surrounded by rings of colour, passing into a white towards the centre of the grain, if this is of sufficient thickness.

The colours seen between crossed nicols are at their brightest when the vibration-traces of the mineral, whether a plate or wedge, are arranged at 45° with those of the nicols. It is clear that there is nothing to cause the actual colour to change during a rotation, since the thickness of the section producing it remains the same. It merely loses intensity towards the positions of extinction and revives after they are passed.

The colour cannot, however, be the same for all plates of the same thickness cut from the same crystal, since these may have various directions in regard to the original crystal, and consequently the relative retardations produced in the two sets of rays are not necessarily the same. The *interference-colour* varies, therefore, with the thickness of the plate and with its orientation in the crystal.

The colours of the thin end of a doubly refracting wedge, or of thin plates, are called *low colours*. They are at the low end of Newton's scale of interference-colours,[1] and indicate weak double refraction. As we ascend the scale, that is, as the plate thickens, we reach *high colours*, that is, colours of the higher orders of Newton's scale; these indicate a marked difference in retardation between the two sets of rays, or strong double refraction.

In ordinary thin sections of rocks, where sections of the same mineral present themselves cut in various haphazard directions, the majority of the sections of one mineral will show high colours, while those of another will show low colours. The conclusion is that the former mineral has strong double refraction, or *birefringence*, as compared with the latter one, the thicknesses of the sections of each being the same. The colours of Newton's scale, again, will be more spread out in a wedge of quartz than in a wedge of calcite of the same angle, since a smaller thickness of the latter suffices to give a colour high up in the scale.

Twin crystals of doubly refracting minerals will be easily revealed in rock-sections owing to their component parts being in most cases traversed in different directions by the section.

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[1] See the beautiful coloured plate at the end of Lévy and Lacroix, "Les Minéraux des Roches," or of Iddings, "Rock Minerals."

Hence the surface of junction of the components will separate two differently coloured areas, one of which may be extinguished while the other remains illuminated. It is, however, possible to find twins which yield simultaneous extinctions for their component parts in certain sections.

Optical sign. Determination of the vibration-traces of the slow and fast rays respectively in a crystal-plate or a small crystal.

The fact that the interference-colours rise towards the thick end of a wedge cut from a doubly refracting mineral provides a simple means of determining which of the vibration-traces in a crystal-plate belongs to the slow rays and which to the fast rays. Other methods may be used, but the *quartz wedge* alone requires description here. The wedge, if cut so that its length is parallel with the optic axis of the crystal, has one of its vibration-traces parallel with its length and the other perpendicular with it. The slow rays emerge from the wedge vibrating parallel with its length.

If a crystal-plate or a small transparent crystal is brought into a position of extinction between crossed nicols, and then rotated through 45°, its vibration-traces will lie at 45° with those of the nicols. The quartz wedge may be moved across the field with its length parallel with one or other of the vibration-traces of the object. If a low-power objective is used, the wedge may be pushed in directly above the object; but for greater convenience slots are usually cut in the tube of the polarising instrument above the objective, and the wedge is slid through these in the desired position.

If the vibration-trace tested is that of the slow rays in the object, the effect of the wedge, as it is pushed into the field, will be merely to raise the colour shown by the object. The vibration-traces in the wedge and in the object correspond, slow with slow and fast with fast. A greater difference of retardation is imparted to the two sets of rays. It is as if a thickening of the object had taken place. If, on the other hand, the vibration-trace of the slow rays in the object are parallel with those of the fast rays in the wedge, the wedge produces a relative acceleration of the slow rays and a retardation of the fast rays from the crystal. The interference-colours are thus lowered, and a thickness of the wedge is ultimately reached which produces a *compensation* of the difference of velocity in the two sets of rays from the object. A dark band crosses the wedge where this occurs, and indicates the abolition of any effect due to double refraction.

On either side of this dark band the colours rise in Newton's scale, and this is the best evidence that compensation has occurred when the wedge is pushed in across a small object. The grey tint due to lowering of the interference-colours may be momentarily overlooked; but the succeeding rise of colour causes the observer to draw back the wedge and repeat the experiment. The thickness of quartz required to produce compensation obviously provides a measure of the birefringence of the object for the particular direction under examination.

The quartz wedge is one of the most useful additions to the ordinary polarising microscope. Dr. J. W. Evans[1] has devised a double wedge, formed of two quartz-wedges of the same slope laid side by side. One longitudinal half of this combination is so cut that in it the direction of the vibration-trace for the slow rays is perpendicular to that in the other half. The effect due to the birefringence of the object can be estimated by observing, in that half of the compound wedge whose vibration-traces coincide in character with those of the object, the tint that lies opposite the dark band in the other half. This tint is double that which would be due to the birefringence of the object alone.

Special Optical Characteristics of Uniaxial Crystals.

As previously stated (p. 94), the ordinary ray in uniaxial crystals has a constant index of refraction and lies in the plane of incidence of the ray falling on the crystal. If the angle of incidence is 0°, that is, if the ray is normal to the surface, the ordinary ray pursues the same course in the crystal. In the case of an oblique ray, the vibrations of the ordinary ray in the crystal take place perpendicular to the plane containing the ray and the optic axis.

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[1] "On Some New Forms of Quartz-wedge and their Uses," *Min. Mag.*, **14** (1905), 91. On combination-wedges, see F. E. Wright, "A New Ocular for use with the Petrographic Microscope," *Amer. Journ. Sci.*, **29** (1910), 416; also *Journ. Geol.*, **10** (1902), 33.

In most sections, the extraordinary ray is refracted from the course of the incident ray, even though the latter is normal to the surface. This is clearly illustrated by laying a cleavage-form of calcite over a black spot marked on a piece of paper. On looking down vertically on the upper surface, which is parallel with that in contact with the spot, and rotating the calcite, one of the two images of the spot rotates round the other. This is the image formed by extraordinary rays.

If a cleavage-form of calcite is ground so that two end-planes are added to it perpendicular to the optic axis, the spot can be viewed through these planes down the optic axis. Only one image is formed, and its position is unchanged during rotation. In this direction the ordinary and extraordinary rays have the same velocity; if, by refraction of an incident ray at a face oblique to the optic axis, the refracted ray is caused to travel up the optic axis, only one refracted ray is formed, and its refractive index is found to be that of the ordinary ray. If the incident light is ordinary light, that is, light in which the vibrations take place in all azimuths, the ray is not polarised by the crystal, since all directions perpendicular to the optic axis are equivalent vibration-directions in the crystal. It emerges, therefore, still as ordinary light.

If, however, the incident light is plane-polarised, as when a polariser is introduced below the object, it emerges as plane-polarised light, but without double refraction. In certain cases *rotatory polarisation* occurs, and the vibration-plane of the emerging light is not parallel to that of the incident rays from the polariser.

The optic axis, however, is not the only direction in which the rays from an object on the far side of a uniaxial crystal travel along the same path and consequently furnish only one image. This may be demonstrated in calcite, where the birefringence of the mineral is so strong as to lead us to expect two images to be formed with a comparatively small specimen. If the incident light is normal to a plane of a uniaxial crystal which is parallel to the optic axis, and emerges at a second plane parallel with this, double refraction in the technical sense takes place, but the two rays follow the same path, normal to the optic axis. A spot viewed normally through two parallel prism-planes in calcite thus gives only one image, and in this respect every direction perpendicular to the optic axis is equivalent. But two sets of rays are formed, as may at once be proved between crossed nicols, by the occurrence of positions of extinction. The quartz-wedge will show that one of these sets of rays has a less velocity than the other. The difference of velocity for this direction of the rays in the crystal is, in fact, as great as possible. The vibration-directions determined by the positions of extinction are those of the fastest and slowest rays in the crystal.

These vibration-directions are found to be parallel and perpendicular to the optic axis. The rays vibrating parallel with the optic axis are the extraordinary rays. When these are the slowest rays, the crystal is styled *positive;* when they are the fastest, it is styled *negative.* The positive character of a uniaxial crystal may be seen from the expression of its birefringence. Thus, $\epsilon - \omega = 0{\cdot}009$ in quartz; while in the negative mineral calcite we have $\omega - \epsilon = 0{\cdot}172$. Here ϵ is at once seen to be the slowest ray in quartz and the fastest ray in calcite.

Neither of the rays undergoes refraction in the above experiment, and the two are recognised only by their vibrating in planes perpendicular to one another and by their difference of velocity. The strength of the birefringence can be estimated by the colour-effects between crossed nicols. The refractive indices of the crystal for ordinary and extraordinary rays traversing it in this direction can be determined by causing the incident light to fall obliquely on a prism-face of the crystal and so that the plane of incidence is perpendicular to the optic axis. Two diverging rays are now formed in the crystal, and both, under these conditions, lie in the plane of incidence. Either one or other can be caused to traverse the crystal perpendicular to the optic axis, by rotating the prism in regard to the incident ray. If a triangular prism is cut from the mineral with its angles 60°, and its axis parallel with the optic axis, the angle of refraction of either ray can be observed in the ordinary manner, monochromatic light being used, and the prism being set so that the ray to be determined passes through the prism perpendicular to its axis and parallel with one of its prismatic faces, that is, in the position of minimum deviation.[1]

From the above considerations it follows that (i) *a section of a uniaxial crystal cut perpendicular to the optic axis remains dark throughout a rotation between crossed nicols*, except where rotatory polarisation occurs. In ordinary thin sections, moreover, the rotation of the vibration-plane by crystals possessing rotatory power is so slight that the section remains dark between crossed nicols.

When a section perpendicular to the optic axis is 1 mm. or more in thickness, light is seen throughout a rotation, whether the mineral has rotatory power or not. This is due to the rays that traverse the section obliquely to the optic axis, owing to our imperfect methods of illumination. When the section, however, is thin, the difference of retardation produced for these particular directions of the two rays into which each oblique incident ray is divided is not sufficient to produce an appreciable difference of phase.[2]

(ii) All sections parallel wtth the optic axis will, for equal thicknesses, display the same interference-colour between crossed nicols, and this will be the highest colour obtainable from the particular mineral in sections of this particular thickness.

As stated above, the effects due to *rotatory polarisation* are not commonly seen by geological workers; but they are remarkable in thick sections of the common uniaxial mineral quartz, cut perpendicular to the optic axis. Such sections show a colour between crossed nicols, varying with the thickness, and give no extinction on rotation. The colour is due to the fact that the angle of rotation of the vibration-plane of the rays from the polariser is markedly different for light of different colours, the violet rays having their vibration-planes most rotated. The direction of rotation agrees with the right-handed or left-handed character of the crystal examined (p. 198). In Fig. 66 the vibration-plane of the violet rays VV is shown to be so rotated to the right from its original direction PO that it almost again coincides with PO. That for the red rays, RR, deviates but little from PO in a right-hand or clockwise direction. Rays of some intermediate colour, here between yellow and green, vibrate parallel with the plane of transmission of the analyser, AN. These rays are in consequence transmitted by the analyser without loss of amplitude, while the violet and red rays are both much nearer the position of rejection. The eye, then, appreciates the prevalent colour, here a yellow-green. If the polariser is rotated to the right, the colour changes, since vibration-directions for rays of successive colours are brought in turn parallel with AN. In this case, when the nicols are, as we say, parallel, that is, when PO is parallel to AN, the prevalent colour is a red-violet.

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[1] See Tutton, "Crystallography" (1911), 582 and 728.

[2] See investigation by C. Travis, "On the Behavior of Crystals in light parallel to an Optic Axis," *Amer. Journ. Sci.*, **29** (1910), 433.

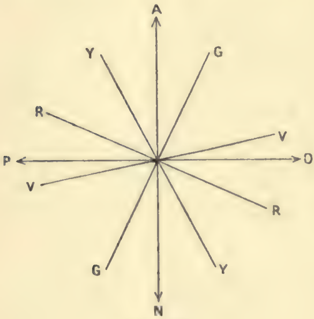

FIG. 66.

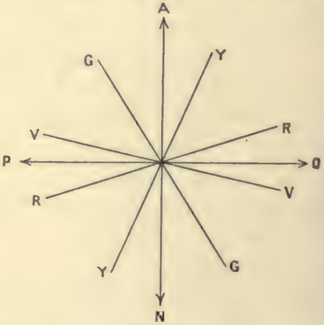

FIG. 67.

The conditions in a left-handed crystal of similar thickness, and therefore giving the same colour, are seen in Fig. 67. The right or left handed character of the crystal can be determined by the order in which the colours follow one another when the polariser is rotated to the right. The whole wheel of the vibration-directions for differently coloured rays is then turned also to the right, and successive colours are brought parallel to the plane of transmission of the analyser.

The colours due to rotatory polarisation are thus not due to interference, but result from the predominance of rays of a particular tint after the rejection of others by the analyser.

Special Optical Characters of Biaxial Crystals.

In biaxial crystals, as stated on p. 94, we have to deal with two directions along which no double refraction takes place. Rays vibrating in any azimuth about these *primary optic axes* pass through the crystal with equal velocity; but these directions have one important difference that distinguishes them from the optic axis of uniaxial crystals. A beam of rays, vibrating in all directions, incident normally on a plate of a biaxial mineral cut perpendicular to an optic axis is not transmitted as a compact beam along the axis. The only rays transmitted exactly along the optic axis are those vibrating perpendicular to the optic axial plane, while the others form a hollow cone of small angle, emerging in a circle on the upper surface of the plate. The optic axis and the ray travelling along it lie on the surface of this cone, the other rays being variously refracted on the conical surface, and thus travelling with different velocities. If plane-polarised light is employed, it is clear that it will travel in the crystal along some one of these directions without double refraction, the direction being determined by its direction of vibration in regard to the optic axial plane. If before entrance it vibrates parallel with this plane, the ray will travel in the same plane in the crystal, along a path that differs from the optic axis by the angle of the cone (Fig. 68).

On emergence, the circle of rays forms a hollow cylinder, the axis of which is parallel with the primary direction of the rays, that is, it lies normal to the surface of the plate. The optic axis is thus continued along one side of this cylinder (Fig. 68). Since the optic axis is merely a direction and not a set line in the crystal, at every point on the surface, when ordinary light is used, rays emerge vibrating in all directions, through the overlapping of innumerable circles of rays.

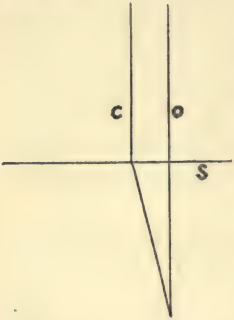

FIG. 68.—Section of biaxial crystal S parallel with the optic axial plane, with emergence of the plane-polarised rays O and C from the surface of the crystal-plate. O vibrates perpendicular to the optic axial plane; it has entered the crystal parallel with the optic axis, and travels in the crystal in the same direction. C vibrates parallel with the optic axial plane; it has also entered the crystal parallel with the optic axis, but undergoes refraction, emerging again parallel with the optic axis.

When, however, plane-polarised light is employed, its plane of vibration is unchanged, though the rays are usually refracted; the case in which they are not refracted is when their vibration-direction is perpendicular to the optic axial plane. Hence the section should appear dark between crossed nicols, like that of a uniaxial mineral cut perpendicular to the optic axis. *A section of a biaxial mineral, however, cut perpendicular to an optic axis does not appear dark, nor can it be extinguished during a rotation.* As Wülfing points out,[1] this might be accounted for by the fact that the optic axes are not the same for light of all colours. Hence some of the light suffers double refraction by not being directed along the optic axis for its particular colour. But this is not enough, since the section remains illuminated even when light of the colour appropriate to it is used. Hence both Wülfing and C. Travis[2] rely on the explanation that our methods of illumination give rise to oblique incident rays as well as those normal to the surface of the section. The components of these in biaxial crystals are refracted with a sufficient difference of velocity, even when they are only slightly inclined to the optic axis, to allow of the emergence of rays of certain colours in opposite phases and so of their transmission by the upper nicol.

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[1] Rosenbusch-Wülfing, "Mikroskopische Physiographie," **1**, part i. (1905), 240.

[2] "Behavior of Crystals in Light parallel to an Optic Axis," *Amer. Journ. Sci.*, **29** (1910), 430.

In the plane of the primary optic axes, and nearly coincident with them, there are two directions known as *secondary optic axes.* Light passing along these has the same velocity whatever its direction of vibration ; but a beam so travelling emerges into air as a divergent cone of rays. Any effect due to these axes is in practice superposed upon that due to the primary optic axes, and J. P. Iddings[1] attributes the light seen when sections perpendicular to an optic axis are viewed between crossed nicols to the obliquity of the emerging rays, which enables them to escape total reflection in the upper nicol.

L. Fletcher[2] more exactly styles the primary optic axes *optic binormals*, and the secondary optic axes *optic biradials.* When the term "optic axes" is used alone, it always refers to the primary pair.

The plane containing the optic axes, as previously stated, is known as the *optic axial plane.* The line bisecting the acute angle between the optic axes is the *acute bisectrix*, and the line perpendicular to it and also in the optic axial plane is the *obtuse bisectrix.* The *optic axial angle* is the acute angle between the optic axes ; it may sometimes be near 90° or sometimes very small. In the latter case, sections perpendicular to the acute bisectrix reveal very nearly uniaxial conditions between crossed nicols.

The two rays due to double refraction that can travel in the crystal perpendicular to the optic axial plane vibrate respectively parallel to the two bisectrices, and are the fastest and slowest rays in the crystal; their refractive indices are thus respectively α and γ (compare p. 95). When the slowest ray vibrates parallel with the acute bisectrix, the crystal is said to be *positive;* when the fastest ray does so, the crystal is *negative.*

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[1] "Rock Minerals," ed. i. (1905), 172.

[2] *Min. Mag.*, 9, 338.

As in uniaxial crystals, these terms are somewhat unfortunate, since they convey no meaning in themselves.

A section cut parallel with the optic axial plane shows, by its positions of extinction, and therefore by its vibration-traces, the positions of the two bisectrices; but it does not show which of these is the acute bisectrix. This can only be determined in sections perpendicular to the optic axial plane, viewed in convergent polarised light, as may be seen from later paragraphs of the present chapter.

The section parallel with the optic axial plane obviously exhibits the strongest birefringence in the crystal. Its two vibration-directions are those of the fastest and the slowest rays, which we expressed by the German symbols $\mathfrak{a}$ and $\mathfrak{c}$, or the French n_p and n_g, when dealing with pleochroism on p. 113. Any section of the zone of which $\mathfrak{a}$ is the zone-axis will have one of its vibration-traces parallel to $\mathfrak{a}$, and the other of course perpendicular to it (Fig. 61). The ray vibrating parallel to $\mathfrak{a}$ and travelling in the crystal perpendicular to the surfaces of the section will have in all sections from this zone the refractive index α. The refractive index of the other ray, travelling in the same direction in the crystal, will vary with the orientation of the section, being γ, as above stated, when the section is parallel with the optic axial plane, and β, the approximately mean index, when the section is perpendicular to this plane.

Similarly, all sections in the zone of which $\mathfrak{c}$ is the zone-axis have one of their vibration-traces parallel to $\mathfrak{c}$. The ray vibrating parallel to $\mathfrak{c}$ and travelling in the crystal perpendicular to the surfaces of the section has in all such sections the refractive index γ. The refractive index of the other ray varies with the direction of the section from α to β.

In the zone the axis of which is perpendicular to the optic axial plane, all sections have one of their vibration-traces parallel to $\mathfrak{b}$ (or n_m), and the ray vibrating parallel to $\mathfrak{b}$ and travelling in the crystal perpendicular to the surfaces of the section has in all such sections the refractive index β. The refractive index of the other ray varies with the direction of the section from α to γ.

Hence the birefringence, and consequently the interference-tint for a given thickness of section, vary considerably with the orientation of the section in regard to the crystal.

In Fig. 69, three planes, P, Q, R, perpendicular to one another, intersect in lines which we may make proportionate, for graphic representation, to the three refractive indices, α, β, and γ, of any crystal. These lines, in the directions previously styled $\mathfrak{a}$, $\mathfrak{b}$, $\mathfrak{c}$, may now be named, following a suggestion made by Mr. L. Fletcher to the author, the α-axis, the β-axis, and the γ-axis. This may be preferred to the French system, or that proposed by F. E. Wright, of representing the directions merely by the same symbols as those used for the refractive indices. In the figure, P is evidently the optic axial plane, since it contains both the α and the γ axes. Of the two rays of any pair that can be propagated in the plane Q, one will be "ordinary," having for all directions the refractive index α; it vibrates parallel to the α-axis. Similarly, for the plane R there is an "ordinary" ray with index γ and vibrating parallel to the γ-axis; while for the plane P there is an "ordinary" ray with index β and vibrating parallel to the β-axis. The planes shown in the figure are, then, the three that must be taken into account when the refractive indices of a biaxial crystal are being determined.

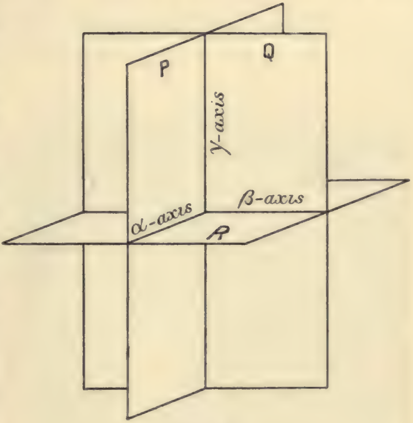

FIG. 69.

When a crystal-section is parallel with any one of these planes, an incident ray *normal to the surface of the section* gives rise to two rays of different velocities, but propagated along the same line. No bending takes place, and the rays continue normal to the second parallel surface on emergence. In a section parallel to P, for example, fast and slow rays travel along the β-axis, with velocities inversely proportional to α and γ respectively.

Representation of the Optical Characters of a Mineral by the Indicatrix.

In Fig. 69 a step was made towards the geometrical representation of the optical characters of a biaxial crystal, and we may now refer briefly to the *Optical Indicatrix*, a surface of reference devised by L. Fletcher in 1891,[1] and now as widely recognised and adopted as is Miller's notation of crystal-faces. In place of the three planes drawn in Fig. 69, a triaxial ellipsoid may be constructed, with its three axes proportional to the determined values of the refractive indices α, β, and γ for a particular biaxial mineral (Fig. 70). This ellipsoid is the indicatrix for that

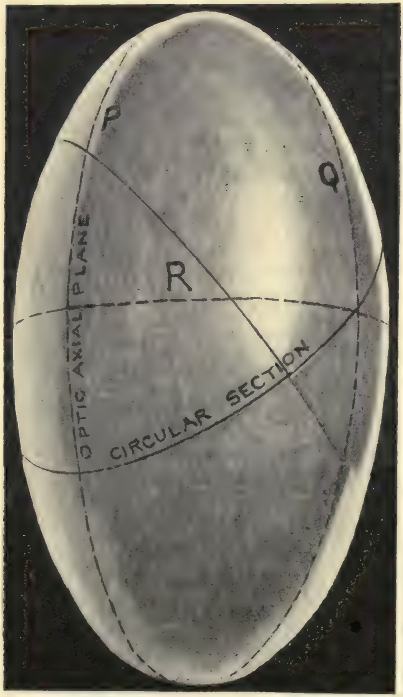

FIG. 70.—Indicatrix for a biaxial crystal (from a wooden model by Krantz of Bonn, marked to correspond with the present text).

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[1] *Min. Mag.*, **9**, 278–388, and, as a separate work, "The Optical Indicatrix and the Transmission of Light in Crystals," with a historical introduction, published by H. Frowde, 1892.

mineral. The section of the ellipsoid by a plate cut from a mineral is in general an ellipse, and the two axes of this ellipse indicate the *traces of the vibration-planes* of the two plane-polarised rays that result from the double refraction of a ray entering the crystal-plate normal to its surface. Since these rays again become normal to the surface on emergence into an isotropic medium, the vibrations of both take place on emergence parallel to the surface of the crystal-plate, and the axes of the ellipse thus represent the actual *directions of vibration* in the air.

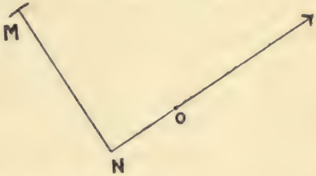

FIG. 71.

The refractive indices of these slow and fast rays for the particular section are, however, not usually recorded by the lengths of the axes of the ellipse. The construction of the indicatrix is such that if any ray be conceived as passing through its centre O (Fig. 71), and a line MN be drawn perpendicular to the ray and also to the surface of the ellipsoid, this line represents by its length the refractive index of the ray, and is therefore inversely proportional to its velocity.

The vibrations of the ray will take place in the plane containing MN and the ray, and, since the vibrations are perpendicular to the ray, MN will represent their direction. To put it another way, if from any point M on the indicatrix we drop a perpendicular to its surface, that is, to the tangent-plane at that point, and draw from this line another line NO perpendicular to it and passing through O, the centre of the indicatrix, this second line gives the direction of the ray which vibrates parallel to MN in the plane MNO and has a velocity $= \frac{1}{MN}$.

If the plane of the crystal-plate happens to be parallel to two of the axes of the indicatrix, that is, to one of the three *principal sections of the ellipsoid*, rays incident normally to its surface are not bent out of their course. Two sets of rays are formed, propagated along the same path, and the axes of the ellipse formed by the intersection of the plate and the ellipsoid represent, in such a case, not only the vibration-directions of the two rays, but, in inverse proportion, their velocities. They are also directly proportional to the refractive indices of the rays vibrating parallel to them respectively. These refractive indices can be measured experimentally by causing the fast and slow rays of a pair formed by double refraction at a surface oblique to the principal section to travel in the crystal in turn along the direction perpendicular to the principal section; and it is, indeed, from these determinations that the indicatrix is constructed.[1]

In the ordinary case, however, where the crystal-plate is oblique to the principal sections of the ellipsoid, the two rays formed from the normally incident ray are not in the crystal normal to the surfaces of the plate. Hence the lines perpendicular to their directions and to the surface of the ellipsoid (see MN in Fig. 71) do not lie in the elliptical section; it is these lines, however, that represent the refractive indices of the two rays.

We may now consider more closely the characters of the three principal sections of the indicatrix. Each is an ellipse, and contains as its axes two of the axes of the indicatrix. At Mr. Fletcher's suggestion, as already noted, we may call these axes the α-axis, the β-axis, and the γ-axis. They are the X, Y, and Z axes of Iddings. The optical characters of a crystal-plate parallel to P (Fig. 69), the optic axial plane, are represented by an ellipse with axes equal to α and γ. The plate parallel to R cuts the indicatrix in an ellipse which has axes equal to α and β. Plates in intermediate positions in the zone of which the α-axis is the axis will form ellipses one axis of which will always equal α, while the other is always longer, its limits being γ and β. Similarly, for plates of the zone the axis of which is the γ-axis, ellipses arise with one axis always equal to γ, and the other always shorter, its limits being α and β. But a special feature arises in the zone of crystal-plates the axis of which is the β-axis, that is, the zone perpendicular to P, the plane containing the α and γ axes. In a plate from this zone parallel to the plane Q, two rays can be propagated along the α axis, which have the indices β and γ respectively. In a plate parallel to the plane R, the indices are α and β. Plates in intermediate positions in this zone have one index always equal to the mean index β, while the other varies between the extreme indices α and γ. Hence for some inclination of the plate the two indices are both equal, and the ordinarily elliptical section of the indicatrix becomes a circle. There are, moreover, two such *circular sections*, inclined to one another at an angle which depends on the proportions of the indicatrix (Fig. 70). Since the rays with which we are dealing are those propagated along the line perpendicular to the section, it is clear that for the directions in the crystal perpendicular to the circular sections, there is no difference of refractive index. Rays vibrating in any azimuth are transmitted along these directions with the same velocity. *These directions are the optic binormals or optic axes.*

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[1] See A. E. H. Tutton, "Crystallography" (1912), 726.

In the case of a uniaxial crystal, the indicatrix is an ellipsoid of revolution, and its axis of revolution is made equal to the refractive index ϵ, which is that of the extraordinary ray. Hence in negative crystals this axis is less than the horizontal diameter, which is equal to ω, and it is greater than the horizontal diameter in positive crystals. All crystal-plates parallel with the ϵ-axis cut the indicatrix in similar ellipses, the axes of which equal ϵ and ω, and the rays formed by double refraction and travelling perpendicular to the surfaces of the plate vibrate parallel respectively to these axes. A plate perpendicular to the ϵ-axis cuts the indicatrix in a circle. For such a plate there can be no double refraction. It corresponds in some respects with the plates that make circular sections of the indicatrix in biaxial crystals, and the line along which rays normal to its surfaces are propagated is the *optic axis* of the crystal.

Positions of the Optic Axial Plane in Biaxial Crystals. Dispersion of the Optic Axes.

In crystals of the *rhombic* system, the optic axial plane always includes two of the crystallographic axes. In crystals of Class I it may therefore be any one of the planes of symmetry. The optic axes are equally inclined to the two axes of crystallographic form in the optic axial plane, which are thus the bisectrices ; but there may be a difference of position of the optic axes in this plane for light of different colours. Such "dispersion" is symmetrical with regard to the bisectrices ; that is, the bisectrices remain the same for light of all colours. The optic axial angle for violet light may be smaller or larger than that for red light, according to the mineral species. The indicatrix remains the same for light of different colours in regard to the position of its three axes, but its dimensions may vary for different colours. In some rare cases, such as brookite, the optic axial plane is not the same for light of all colours, though it is always one of the planes of symmetry.

In crystals of the *monoclinic* system, the optic axial plane is either the plane of symmetry or some plane perpendicular to it. But the bisectrices may not coincide for light of different colours. When the optic axes lie in the plane of symmetry, they and the bisectrices may be dispersed in this plane (*inclined dispersion*). Since the position of the bisectrices is thus shifted in the optic axial plane, it is clear that the indicatrix, which has the bisectrices for two of its axes, cannot have the same axes for light of different colours. One of its axes, however, remains constant, that is, the β-axis, perpendicular to the optic axial plane.

The optic axial plane in other monoclinic minerals may differ in position for light of different colours, which may be the case when the b crystallographic axis is one of the bisectrices. The other bisectrix is now dispersed by the rotation of the plane about the b-axis for different colours. If we conceive the optic axes as having ends, these ends form a pair about each of the four ends of the bisectrices. The two ends of any pair about the end of a bisectrix that undergoes dispersion will be swung for one colour equally away from their position for another colour and in the same direction ; while the two ends about an end of the bisectrix which serves as the axis of rotation will be swung for one colour equally away from their position for another colour, but in opposite directions. Here again, the indicatrix cannot have the same axes for different colours ; but one of its axes, corresponding with that of rotation of the optic axial plane, will remain constant.

When the acute bisectrix is that which undergoes dispersion, the dispersion of the optic axes is said to be *horizontal*. When it coincides with the axis of rotation of the optic axial plane, the optic axes are said to undergo *crossed dispersion*.

If the optic axes and bisectrices are drawn on two cards in precisely similar positions, and the cards are held so that a bisectrix in one of them is in a line with the corresponding bisectrix in the other, and one card is then rotated about this bisectrix, the above statements will be obvious.

In the *triclinic* system, the position of the optic axial plane has no relation to the crystallographic form, and the dispersion for light of different colours is entirely unsymmetrical.

Observations with Convergent Polarised Light.

By means of a converging lens placed between the polariser and the object, plane-polarised light may be converged as a cone within the object, emerging as a converging or a diverging cone of rays, according to the distance at which the converging lens lies below the object. In all cases it is necessary that this lens should be readily brought in or out of operation, and it is sometimes convenient if it can be raised or lowered, as is the case with an ordinary substage condenser.

Let us deal at first with an isotropic plate, say of glass or fluorspar. The light is converged from below so as to emerge as a convergent cone. The rays in the centre of the field of view come up normally from the surface of the plate to the objective; but those away from the centre are converged at angles that deviate more and more from the normal as they lie farther from the centre. Hence the plate cuts the cone of rays so as to make circular sections of successive cones, along the surfaces of which rays are travelling. In any circle, then, round the centre of the field of view, rays are emerging that have travelled along paths of the same length in the object; but for successive circles these paths become longer as we pass outwards from the centre.

If the plate is doubly refracting, it is clear that it cannot show the same interference-colour over its whole surface. Owing to the convergence of the rays that traverse it, at some points the relative retardations for rays of a particular colour in the groups of slow and fast rays produced will be much greater than at points nearer the centre of the field. The longer paths followed by the rays as we pass farther from the centre correspond to a thickening of the crystal-plate in observations with ordinary parallel polarised light, and higher interference-colours will be produced. The colours will be arranged in successive orders of Newton's scale in a series of rings or approximations to rings. Moreover, the vibration-traces of the pairs of emerging rays differ at different points, since pairs of these rays, owing to the convergence, have traversed the crystal in two directions which are not the same for every point upon the surface. In considering these directions, we have to remember the refraction of the converged rays as they enter the plate, although they finally emerge in the original directions imparted to them by the converging lens.

Since the incident light is plane-polarised, it will at some points enter the crystal-plate vibrating in one or other of the two vibration-planes offered by the crystal for rays of this particular incidence. In such cases the rays will not be doubly refracted, and will produce no effect between crossed nicols. Such points occur in series across the section, and a dark band will appear passing through them. Since adjacent points on either side of the band will produce nearly the same effect, the band will be widened out into dusky fringes, shading off into the coloured areas of the section. From these considerations, we may expect in convergent polarised light an interference-effect consisting of some arrangement of coloured rings or curves associated with bands of darkness.

Uniaxial crystals are best studied in convergent polarised light in sections perpendicular to the optic axis. Biaxial crystals are best studied in sections perpendicular to the acute bisectrix. But geological workers have often to be content with sections of minerals, occurring in thin rock-slices, which approach only distantly to these ideal conditions. Selected sections of greater thickness, say 1 mm. to 2 mm., which are cut for the illustration of the characters of special minerals, should accordingly be examined before convergent light is applied to the unknown chances of rock-slices. Such sections can be obtained from Krantz of Bonn, or other mineral dealers, or, as is still better, they may be prepared by the student without much difficulty from fair-sized translucent crystals. For a biaxial example, nothing is more effective than a thick plate of muscovite mica (not phlogopite, which is also used commercially, and which is nearly uniaxial). Such a plate can be gradually thinned down by flaking, and the changes in the convergence-picture, due to varying thickness, can be noted.

The image formed when the converging lens is used does not come within the focus of the eyepiece of the microscope. It may be viewed by the insertion of a lens between the surface on which it is focused and the eyepiece. This is mounted so as to slide in and out of a slot in the tube of the microscope, and is known as the *Bertrand lens*. The convergence-picture can, however, be well seen, as Michel Lévy showed, by removing the eyepiece; it is then small but brilliant, and its features are far more sharply defined than when magnified by the eyepiece. A fairly high power is required in the objective when thin sections are examined, and an eighth-inch power should be kept available. The wide angle covered by such an objective enables a more complete picture to be obtained.

The importance of the use of convergent polarised light lies in the distinction revealed between uniaxial and biaxial minerals, and in the possibility it affords of measuring the angle between the optic axes in sections of the latter perpendicular to the acute bisectrix. If the light from the polariser is converged through a plate of a *uniaxial* mineral cut perpendicular to the optic axis, a black cross is seen, its arms being parallel to the vibration-directions of the nicols and its centre coincident with the centre of the field. This cross does not change when the plate is rotated, or when the nicols are rotated together in their crossed position. If the section is thick, or if the mineral possesses strong birefringence, coloured rings, concentric about the centre of the cross, are also seen. With monochromatic light, dark and light circles alternate. In either case, the circles are closer together in proportion as they lie farther from the centre of the field (Fig. 72).

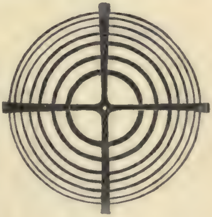

FIG. 72.

In a uniaxial crystal, the vibration-plane for the extraordinary member of any pair of rays is the plane containing the ray and the optic axis; the vibration-plane for the ordinary ray is perpendicular to this (p. 125). Hence in the section examined with convergent light the vibration-traces of the emerging extraordinary rays are in the directions of radii from the optic axis which lies in the centre of the field. At every point on the surface of the section a ray emerges with this radial vibration-trace, and another emerges with a vibration-trace perpendicular to it. These pairs may be diagrammatically represented by the crosses in Fig. 73.

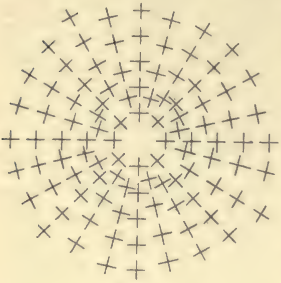

FIG. 73.

Points where the rays emerge with the same amount of relative retardation obviously lie on a circle, and the difference of retardation is greater as we pass outward from the centre to circles where the rays, by greater obliquity, have travelled through greater thicknesses of the crystal-plate. The coloured circles seen with thick sections in white light are thus easily explained, and the colours rise in Newton's scale as the circles become more remote, until they fade away in whiteness. With monochromatic light, the dark circles correspond to regions where the retardation of one ray behind the other amounts to an even number of half wave-lengths of the coloured light employed, that is, to regions where the rays of each pair are emerging in the same phase.

The arms of the black cross pass through points where the vibration-traces are parallel with those of the nicols. No double refraction occurs, as previously pointed out, at such points. When the section is rotated, the cross remains fixed, since new chains of similar points take up the positions of those that now lie in doubly refractive regions. If the crossed nicols are rotated about the optic axis of the section, the cross rotates; but it remains a true rectangular cross. If the section is oblique to the optic axis, the centre of the black cross lies away from the centre of the field, and may even lie outside it. If it is still visible, on rotation of the crystal-plate, it moves in a circle round the centre of the field, carrying the arms with it. The arms remain vertical and horizontal respectively. If the centre of the cross is outside the field, first one arm and then one perpendicular to it move across the field, the arms remaining straight, and parallel respectively to the vibration-planes of the nicols. These observations can be easily made on small sections of granules of quartz in a rock-slice, provided that a high power is used and that a grain is selected that is dark or nearly dark throughout a rotation in parallel polarised light between crossed nicols. Scapolite or tourmaline, from their stronger birefringence, afford still better uniaxial convergence-pictures in rock-slices.

The fact that an optic axis is merely a direction, and that an optic axis emerges at every point in the field, is clearly illustrated when the crystal-plate is moved about under the objective. The convergence-picture remains the same and motionless. The same effect is seen with biaxial plates, provided that they are not rotated during the movement.

In a rock that has undergone deforming earth-pressures, the black cross may be disturbed during rotation of the section, owing to stresses in the crystal, such as those which produce doubly refractive effects in thick masses of glass after cooling down from fusion. In the neighbourhood of flaws in the crystal similar disturbances may be seen.

A section of a *biaxial* crystal cut perpendicular to an optic axis reveals a series of approximately circular rings surrounding the centre of the field, and a black band passing through the centre. As the section is rotated, the black band or bar straightens itself out until it is parallel with one of the vibration-planes of the nicols. It then curves into a hyperbolic form, bending away in a direction opposite to that of the rotation; after 90°, it is again straight, and parallel with the other vibration-plane of the nicols. When straight, the black bar indicates the trace of the optic axial plane on the surface of the plate. The vibrations of the two groups of rays formed by double refraction and travelling in this plane take place perpendicular and parallel to this trace.

Hence no double refraction of the rays from the polariser that emerge on the trace of the optic axial plane occurs when this trace is parallel to either vibration-plane of the nicol. A black bar is seen, and rays emerging on either side, but not parallel with the optic axial plane, have their vibration-traces so little deviated that an approach to darkness occurs, and the bar is widened somewhat. On rotation, the vibration-traces at other points come successively into the position for local extinction, and they lie on a curve passing through the optic axis and symmetrical on either side of the trace of the optic axial plane. When this trace has passed through 45°, it is brightly illuminated, like the line perpendicular to it, and, after another 45°, it is a line along which extinction again takes place. The region of local extinction thus shifts in the field; the black bar seems to curve and swing.

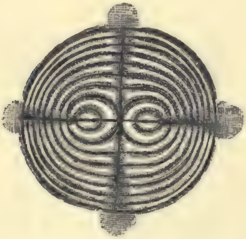

FIG. 74.

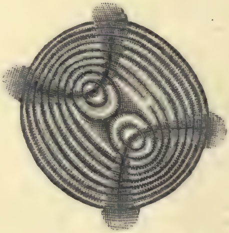

FIG. 75.

To observe the effects due to both optic axes, the section should be cut perpendicular to the acute bisectrix. Two "eyes" are now seen, if the section is thick or if a power of wide angle is used, representing the emergence of two optic axial directions, and surrounded by coloured curves closing round both and known as "lemniscates" (Fig. 74). When the line joining the two eyes, that is, the trace of the optic axial plane, is parallel to a vibration-plane of the nicols, a black bar passes through the eyes, and another broader one crosses it centrally at right angles, in the direction of the β-axis of the indicatrix. The pairs of rays produced by double refraction that emerge in the regions between these cross-bars have their vibration-planes so placed as to give rise to the coloured lemniscates. Along the cross-bars, the vibration-planes for the rays from the converging lens are parallel, and, on either side, nearly parallel, with the vibration-planes of the nicols. Hence these bars represent regions of no double refraction (Fig. 77). On rotation of the plate between crossed nicols, the cross breaks up into two hyperbolic curves or "brushes," symmetrical about the optic axial plane (Fig. 75), and it is again constituted after 90° have been passed through.

This breaking up of the cross forms the most distinctive feature by which a biaxial can be distinguished from a uniaxial mineral in thin sections. The lemniscates may not be visible, but sections can usually be found in which the cross is formed at two positions in a rotation, and is clearly seen to separate into hyperbolæ in intermediate positions (Fig. 76). In plates of muscovite mica this is conspicuous, while biotite gives a figure in which the separation of the hyperbolæ is very slight.

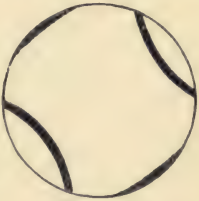

Fig. 76.

Sections perpendicular to the obtuse bisectrix provide less chance of the inclusion of the optic axial eyes within the field. Oblique sections may be distinguished from those of uniaxial minerals by the waving and curving of the dark arms that come successively into view during rotation. This character is of considerable service in discriminating between small clear grains of quartz and felspar in a rock-slice.

The addition of a stage-goniometer to which the plate can be attached so as to rotate about the β-axis enables the observer to view the plate down either apparent optic axial direction successively, and to measure, by the rotation required, the apparent optic axial angle in air, symbolised as 2E. The real optic axial angle (symbolised as 2V) is less than this, since rays passing up the two optic axes in the crystal are refracted still further apart on emergence into the air. The determination of the optic axial angle with convergent polarised light is

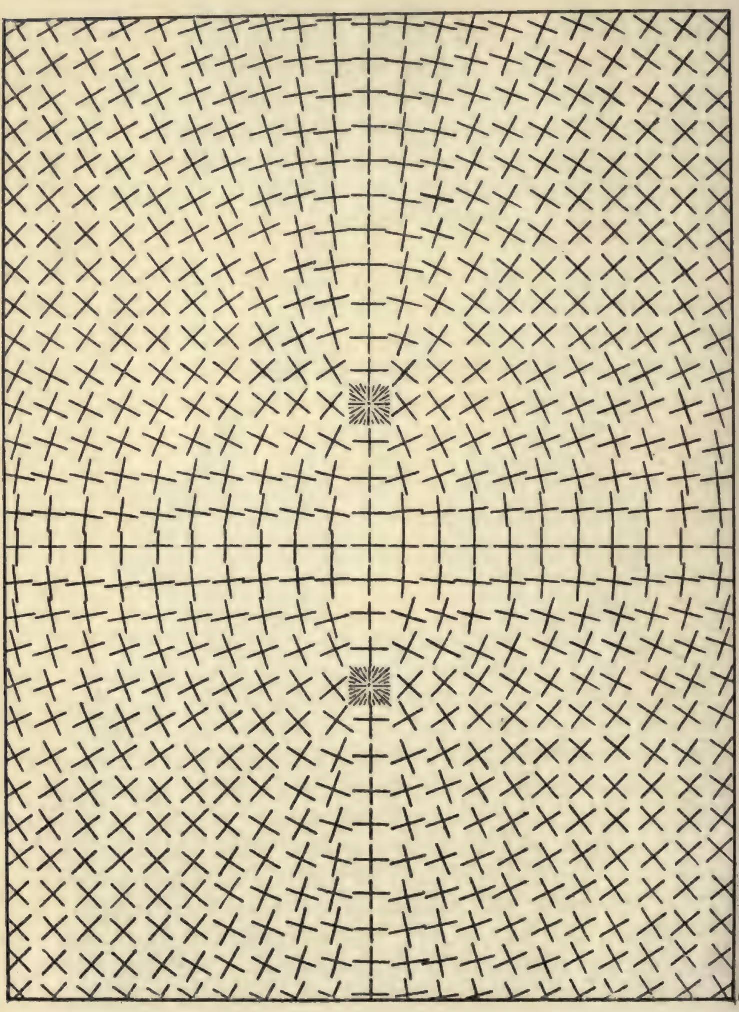

Fig. 77 (see opposite).

dealt with in the larger treatises.[1] The crystal-plate is set with the trace of its optic axial plane at 45° to the vibration-planes of the crossed nicols, since the vertices of the two dark hyperbolæ then mark out precisely the positions of the optic axes that are to be utilised.

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[1] Groth, "Physikalische Krystallographie," 4th ed. (1905), 129; Rosenbusch-Wülfing, "Mikro. Physiographie," 4th ed. (1904), **1** (i.), 323; F. E. Wright, "Methods of Petrographic-microscopic Research," Carnegie Institute (1911), 147; Tutton, "Crystallography," (1911), 766–783; on the latter page a useful table is given illustrating in common substances the difference between the apparent and true optic axial angles.

DESCRIPTION OF FIG. 77.—Diagram constructed by E. G. A. ten Siethoff ("Eine einfache Construction des sogen. Interferenzkreuzes der zweiaxigen Krystalle," *Centralbl. für Min.* (1900), p. 268) to show vibration-directions for rays converged within a biaxial crystal cut perpendicular to the acute bisectrix. If two lines are ruled on a card perpendicular to one another, to represent the vibration-directions of the nicols, and the diagram is rotated above them and in a plane parallel with the card, the form of the dark hyperbolæ for any position can be read off by the crosses that have their arms parallel respectively with the lines on the card.

CHAPTER VII

FURTHER PHYSICAL CHARACTERS

Phosphorescence and Fluorescence.

In most cases the absorption of light by a body causes it to become warmer; but in some cases an excitation occurs which results in the return of light, emanating from the body, and not as a mere reflection. The returned light has usually less refrangibility, that is, greater wave-length, than the light which causes the phenomenon. The body may continue to give out light for some time after the removal of the exciting cause. This character is known as *phosphorescence*, and has been styled *fluorescence* when it occurs only so long as the light is falling on the substance. Uranium-glass and petroleum are examples of fluorescent bodies. Some fluorspar crystals, moreover, are merely fluorescent.

Phosphorescence may also be developed by heating, as in certain cases of fluorspar; or by friction, as in the well-known case of two quartz pebbles rubbed together in the dark. The luminous excitation of minerals placed at the positive terminal of a vacuum-tube, by the beating of electrically charged corpuscles against them, has become familiar since Sir W. Crookes's remarkable researches in 1879.

Since that date the phenomenon has been examined in relation to modern theories of the atom. Zinc-blende, kunzite (a pink spodumene), and other minerals, have, moreover, been caused to emit light under the battery of the particles emitted by radioactive substances.

Radioactivity.

Becquerel having found that salts of uranium affected a photographic plate, by emitting a particular type of radiation, and Madame Curie and Schmidt having independently found in 1898 that salts of thorium possessed similar properties, considerable interest was aroused in the minerals from which uranium and thorium were extracted. The radioactivity of pitchblende, the chief mineral of the uranium series, was found to be due in a slight degree to the uranium, and in a very high degree to the presence of the previously unknown element radium. Two other radioactive elements, polonium and actinium, have since been separated.

Among the minerals recognised as radioactive, pitchblende, a mixture of the oxides UO_3, UO_2, ThO_2, PbO, etc., is by far the most important. Autunite, $Ca(UO_2)_2(AsO_4)_2.8H_2O$, Thorite, $ThSiO_4$, and monazite, $CePO_4$ with $ThSiO_4$, may be mentioned as of geological interest. The question of the bearing of the element radium and radioactivity on geological problems has been dealt with by J. Joly in his well-known work, "Radioactivity and Geology" (1909). On the production of "pleochroic halos" round radioactive minerals, see *ibid.*, p. 64, and also p. 207 of the present book.

Magnetic Properties.

In popular mineralogical usage, a mineral is said to be magnetic when its powder can be attracted by an ordinary bar-magnet. The magnet must be cleaned, to remove anything that might cause the particles to adhere. In practice, the magnetic attraction is manifested by the odd and upstanding positions taken by the fragments on the surface of the steel. If the fragments are placed on a thin paper and the magnet is moved about in contact with the under side, there is no risk of mistaking an irresponsive for a responsive mineral.

But native iron, magnetite, and some specimens of pyrrhotine and ilmenite, are almost the only minerals that respond thus to a bar-magnet. By using an electromagnet and varying the strength of the current, a large number of minerals containing iron, including silicates, can be attracted, and this process has been largely used in the separation of minerals from powdered rock.[1] Magnetite (Fe_3O_4) attracts its own powder, and thus becomes covered with a crust of upstanding fibrous bunches when attacked with a hammer in a lode. Its crystals are often polar, one part attracting and an opposite part repelling the north pole of a compass-needle.

An electromagnet may be constructed so that the two poles point towards one another. When a rod is cut from an amorphous body and hung horizontally, so that it can turn freely between the poles, the application of a sufficiently strong current will cause it by magnetic induction, according to its inherent properties, either to hang with its ends towards the poles of the magnet or to hang crosswise between them.[2] If it adopts the former position, it is styled *paramagnetic*; if the latter, *diamagnetic*. Rods cut from crystals of the *cubic* system in any direction are either paramagnetic or diamagnetic, according to the species. That is to say, though two types occur, each crystal is isotropic in regard to magnetic influence. A sphere cut from a cubic crystal would not rotate between the poles of the magnet, whatever the direction of the thread passed through it for its suspension.

Uniaxial minerals, however, yield rods which vary in their degree of readiness to respond to the magnetic influence. The rod cut parallel with the optic axis, whether the mineral proves to be diamagnetic or paramagnetic, is either the most responsive or the least responsive of the series. A sphere cut from a uniaxial mineral and bored for suspension so that the thread is parallel with the optic axis does not rotate when hung between the poles, since all directions perpendicular to the optic axis are of equal magnetic value.

Biaxial minerals furnish three directions perpendicular to one another which are of different magnetic capacity, two being extremes and one an approximate mean between them. Hence a sphere suspended so that the thread is parallel with one of these directions will rotate until the more responsive of the other two directions comes into the paramagnetic or diamagnetic position, according to the nature of the mineral.

Electric Properties.

The electric conductivity of *cubic* minerals is the same in all directions.

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[1] See T. Crook, *Geol. Mag.* (1908), 560, and J. D. Falconer, *Nature*, **78** (1908), 247.

[2] See Groth, "Physikalische Krystallographie," 4th ed. (1905), 196.

In *uniaxial* minerals, it is the same in all directions perpendicular to the optic axis, and either greater or less in the direction of that axis. The greatest difference in conductivity is between the optic axial direction and any direction perpendicular to it.

In *biaxial* minerals there are two directions showing extreme differences perpendicular to one another, and a third perpendicular to both of these, showing an approximately mean conductivity.

T. Crook (*Mineralogical Magazine*, **15**, 260, and **16**, 109) very ingeniously utilises the difference in the conductivity of mineral species for the separation of fragmental minerals. The mineral mixture, which may be a natural sand, is partly separated by the use of dense liquids (p. 18), and is placed on an electrically charged copper plate. A flat stick of sealing-wax is made electric by rubbing, and is held over the mixture. The minerals that are good conductors of electricity spring up and cling to it, and may be rubbed off into a watchglass. A second copper plate, coated on its under face with shellac, may be used in place of the sealing-wax, and may be electrically charged from an electrophorus. It is placed over the grains and is insulated from the copper plate on which they lie by narrow strips of glass. As an example, cassiterite can thus be picked out from zircon in a heavy residue.

Minerals that become electrically charged on heating are said to show *pyroelectricity*. Electrical axes are developed with a negative pole at one end and a positive at the other, these poles being reversed as the mineral cools down again. The nature of the charge can be determined, as Kundt showed, by spraying the crystal over with powdered sulphur and red lead, forced through a sieve of cotton-wool. By the friction experienced as it is forced out, the sulphur becomes negatively, and the red lead positively, electrified. Hence the crystal draws the sulphur to any portion that is positively charged, and the red lead to any negatively charged portion. In this way yellow and red areas show the distribution of electricity on the crystal.

Tourmaline further illustrates its pyramidal and not bipyramidal symmetry by developing negative electricity at one end of the *c*-axis, and positive at the other. Quartz shows three horizontal electric axes, corresponding with those of its crystallographic form, the positive and negative ends alternating round the series. Under the spray, its vertical prismatic edges thus become coloured alternately red and yellow.

Thermal Properties.

The thermal properties of minerals are closely connected with the optical character of the species.

Cubic minerals conduct heat equally in all directions, and expand equally on heating, so that the angles between their faces do not vary with the temperature. A sphere cut from such a mineral thus remains a sphere. Minerals, however, that are not isotropic at ordinary temperatures may become isotropic at some higher temperature. In cubic minerals there is no double refraction of the heat-rays, which are transmitted without change, whatever their plane of vibration on entering or their direction of transmission.

Uniaxial minerals conduct heat most readily, according to their species, either along the optic axis or in directions perpendicular to it. These two directions are those of the extreme differences of conductivity. Such minerals expand either most or least in the direction of the optic axis, the maximum difference being found in directions perpendicular to this. Some minerals that conduct heat most readily along the axis expand least in this direction. The angles between crystal-faces will obviously change upon heating, except in the vertical prismatic zone ; but two parallel faces remain parallel and a zone remains a zone. The basal planes, moreover, will remain perpendicular to the optic axis.

A sphere cut from a uniaxial crystal becomes on expansion an ellipsoid of revolution with its axis of revolution parallel with the optic axis, and longer or shorter than the diameter of the central horizontal circular section.

When heat-rays are employed in place of light-rays, the thermal characters are seen to agree with the optical ones. There is no double refraction for heat-rays passing along the optic axis, while in other directions two sets of heat-rays are produced, and phenomena of extinction can be observed when a polariscope is employed.

In *biaxial* crystals there are two directions perpendicular to one another along which the maximum and minimum conductivities for heat are manifested. A third direction, perpendicular to the plane of the other two, yields an approximate mean.

In rhombic crystals these three directions correspond with the crystallographic axes. In monoclinic crystals two of the directions are always in the optic axial plane. In triclinic crystals, nothing can be assumed as to the position in which these conductivity-directions will be found to lie.

The crystals expand unequally along these three directions; hence the angles between their faces vary with the temperature. As in uniaxial crystals, however, two parallel planes remain parallel and a zone remains a zone. A sphere becomes on expansion a triaxial ellipsoid.

Double refraction of heat-rays occurs in such crystals, and the optical phenomena are closely followed.

As a simple means of illustrating the relative conductivity of a crystal in different directions, a face may be coated with wax or with some opaque volatile sublimate, such as ammonium chloride; a stout wire is then heated and pressed down endwise on the face. In a cubic mineral the deposit is melted or sublimed away so as to leave a circular area free. In minerals of other systems, an elliptical area arises, and the margin of the ellipse may be sufficiently defined to allow of the measurement of its axes.

Fusion-point. The temperature at which minerals melt has been the subject of many investigations, and the difficulty of observing when fusion actually sets in has given rise to some differences of opinion. The method attended with the greatest accuracy involves the insertion of a thermoelectric couple in the material operated on in the furnace; at the moment of melting, heat is absorbed, and the temperature in the mineral remains for a brief time constant.[1]

The results obtained by Doelter, Joly, and others, employing different methods, show that most rock-forming minerals melt at temperatures between 1000° and 1300°, while some felspars melt above 1500° and quartz and cristobalite at 1600°. Some minerals melt quietly, while others bubble up or intumesce. Some zeolites thus assume fantastic spreading forms, like borax, before actually melting.

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[1] See discussion in J. P. Iddings, "Igneous Rocks," 1 (1909), 82.

Von Kobell devised a rough *Scale of Fusibility*, on the plan of that adopted for hardness by Mohs. Common minerals were selected, and arranged in their order of resistance to the hottest temperature of an ordinary blowpipe-flame. Judging by the ascertained melting-points of minerals that can be fused in a good blowpipe-flame, this temperature must be close on 1500°. The intervals in the scale are decidedly unequal, but the numbers 1 to 6 can be utilised to express the relative fusibility of minerals.

SCALE OF FUSIBILITY.

1. Stibnite. Fuses in a candle-flame.
2. Natrolite. Fuses easily before the blowpipe in considerable splinters.
3. Almandine garnet. The form is soon lost before the blowpipe, all the edges of a fragment becoming rounded.
4. Actinolite. A globule is easily formed before the blowpipe at the end of a small splinter.
5. Orthoclase. Fuses before the blowpipe on thin edges of a splinter.
6. Bronzite. Fuses before the blowpipe at the ends of thin splinters only.

Quartz is infusible before the mouth-blowpipe, and the term "infusible," as used in determinative mineralogy, refers merely to such cases. In the oxyhydrogen flame most "infusible" minerals are fusible with ease, and the amorphous glass produced by the fusion of quartz is now a valuable commercial product.

When comparing the fusibility of minerals before the blowpipe, the hottest part of the flame should be used, that is, the point just outside the inner cone when a good oxidising flame has been produced. It is well to count up to two hundred to oneself during blowing, before deciding that a thin splinter is actually infusible. The product should always be examined with a lens.

CHAPTER VIII

CHEMICAL CHARACTERS

Polymorphism.

WHILE, as was pointed out on p. 4, the chemical constitution of a mineral appears to be its most fundamental character, we are met by the fact that the same chemical substance may produce structures which belong to distinct crystallographic systems. The specific gravity and other physical characters usually differ in these *dimorphous* or *trimorphous* types, and they necessarily rank as independent mineral species. The consideration of the natural conditions under which one or other member of a polymorphous group arises is one of the most attractive objects of research. A member of such a group that is developed under certain conditions may change into a more stable type as time goes on, or as the limiting conditions are removed. It is probable that in members of a polymorphous series we should consider not only the grouping of the molecules in the crystalline structure, but also the grouping of the atoms within the molecules.

Titanium dioxide is thus known in three mineral forms. Rutile and anatase are tetragonal, but with distinct unit forms, the axial ratio in the former being 1 : 0·64415 and in the latter 1 : 1·7771. The third form, brookite, is rhombic. Brookite and anatase have specific gravities close on 4·0, while that of rutile is slightly higher. G. T. Prior,[1] on a comparison of the molecular volumes of similar minerals, suggests that the correct formulæ are as follows: Rutile, Ti_2O_4; Anatase, Ti_4O_8; Brookite, Ti_6O_{12}.

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[1] "Note on a Connexion between the Molecular Volume and Chemical Constitution of some crystallographically similar Minerals," *Min. Mag.*, **13** (1903), 220.

Calcite and aragonite are typical illustrations of dimorphism, the former being the more stable type. Calcite belongs to a remarkable series of allied trigonal carbonates, including siderite and smithsonite. Aragonite is similarly allied by its form to a series of rhombic carbonates, including strontianite and cerussite. This brings us to the subject of isomorphism.

Isomorphism.

It is now certain that the chemical substitution of atoms of one element for those of another element in some or all of the molecules of a mineral produces in all cases a modification in the crystalline form.[1] Absolute isomorphism, that is, identity of axial ratio in crystals of different chemical substances, does not occur outside the cubic system. Yet series of minerals exist in which the similarity of corresponding crystal angles is so close that Eilhert Mitscherlich was justified in regarding them as "isomorphous." Moreover, the elements substituted for one another in his "isomorphous" series are often interestingly allied by their properties, as may be seen when these elements are grouped in Mendeléef's periodic table.

The trigonal carbonates referred to above develop rhombohedra with the following angles over their polar edges :—

Calcite	$CaCO_3$	105° 5′
Dolomite	$CaMg(CO_3)_2$	106° 15′
Siderite	$FeCO_3$	107° 0′
Dialogite	$MnCO_3$	107° 0′
Magnesite	$MgCO_3$	107° 24′
Smithsonite	$ZnCO_3$	107° 40′

The figures recorded for siderite and dialogite suggest true isomorphism. The rhombic carbonates yield the following prism angles :—

Aragonite	$CaCO_3$	116° 10′
Cerussite	$PbCO_3$	117° 13′
Strontianite	$SrCO_3$	117° 19′
Witherite	$BaCO_3$	118° 30′

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[1] See especially A. E. H. Tutton, "Crystalline Structure and Chemical Constitution" (1910), 194.

In estimating the relationships of the minerals in an isomorphous series, it is still better to consider the axial ratios. Thus we have, in a familiar rhombic series:—

Barytes	$BaSO_4$	1·6107 : 1 : 1·2276
Anglesite . . .	$PbSO_4$	1·6422 : 1 : 1·2736
Celestine . . .	$SrSO_4$	1·6432 : 1 : 1·2807

Chemical Changes in Minerals.

The most common changes in minerals at or near the earth's surface are due to oxidation or hydration, which are frequently accompanied by the removal of part of the original mineral in solution. *Pseudomorphs* may thus arise (p. 24), or the mineral may break down into powdery particles, or granules, or fibrous aggregates, which exhibit under the microscope more or less successful attempts at crystallisation in new forms. In most cases chemical changes produce an aggregate that is softer and less coherent than the crystals of the original mineral. An exception is seen in the granular product from the alteration of felspars containing lime, which consists of epidote, zoisite, lime-garnet, and other silicates which individually exceed in hardness the original felspar. A tough and resisting decomposition-product arises in this case.

Chemical Analysis of Minerals.

The examination of a mineral with the microscope convinces one of the necessity for picking out pure material before proceeding to a qualitative or quantitative chemical analysis. Decomposition-patches and inclusions of other minerals have to be avoided, and the few grammes of the substance used must often be selected entirely under the microscope. The methods to be employed are stated in chemical works; but it may be useful to refer to Bulletin 422, by Hillebrand, published in 1910 by the United States Geological Survey, which is a third edition of one issued in 1897, and is specially devoted to the modes of analysing the minerals most frequently met with by geologists. Further revised editions of this may be expected from time to time.

A number of simple qualitative tests assists in the determination of minerals. Their relative solubility in or resistance to common acids is an important character. Boiling in hydrochloric acid thus liberates carbon dioxide from carbonates and sulphuretted hydrogen from sulphides of iron, lead, and zinc. Very few mineral carbonates are decomposed by this acid without boiling, a point that is not always remembered. Both calcite and aragonite, however, effervesce freely in cold acid, and such action usually indicates the presence of one or other of the mineral forms of calcium carbonate.

A few silicates are decomposed by boiling in hydrochloric acid, and some yield their silica in a gelatinous condition as metasilicic acid, H_2SiO_3, which clings to the test-tube used. Wollastonite, $CaSiO_3$, the calcium pyroxene, is thus distinguished from diopside, $MgCa(SiO_3)_2$, by giving an excellent example of this gelatinous residue.

The importance of the mouth-*blowpipe* to the mineralogist and the geologist cannot be overrated. The "dry" tests that can be performed with it and the aid of a stout candle or a grease-lamp, away from the resources of civilisation, often surprise chemists who have learned to rely on the wet tests that are possible in a laboratory. Even in laboratories, it is well to practise with a grease-lamp rather than with gas in the production of the blowpipe-flame. Reductions are, moreover, obtained more easily in the glowing carbonaceous flame of such a lamp. While work proceeds, cylinders cut off a common candle may be dropped into the lamp to feed the flame.

First of all, the mineralogist should practise the production of a prolonged blast through the blowpipe without exertion to himself. Counting slowly to oneself is a great aid to exactitude in blowpipe-operations, since a substance that yields no result to an experienced worker during the counting of two hundred is not likely to give any reaction under the conditions selected for it. A mineral powder dissolved in a borax bead may be regarded as fully reduced or oxidised at the end of such a period, and it will show a characteristic result on cooling if it is ever going to do so. The reduction of metallic minerals on charcoal with sodium carbonate will be effected in a similar time, and the slaggy mass may be then removed and broken up in the hope of finding metal. Most operations are satisfactorily concluded when one hundred only has been counted.

The blast must be produced by the pressure of the cheeks, and not from the lungs. The cheeks can be quietly filled out when air comes from the lungs, and any excess can be expelled through the nose as usual. The aperture in the nozzle of the blowpipe should be circular, and smaller than those usually supplied by dealers. The brass or platinum nozzle can be treated gently with a hammer so as almost to close the aperture, which can then be brought to an admirably circular form by boring it with a large pin.

The cabinets of blowpipe-apparatus arranged by the firm of Letcher of Truro, which include a grease-lamp, have not been surpassed for compactness, and the variety of apparatus and reagents supplied in so small a compass suggests to the user the neatness and economy of material which are absolutely essential in the qualitative work of a prospector.

It may be useful to propose an order in which simple qualitative tests may be undertaken, so that critical reactions may be arrived at without delay. At the same time, a few practical hints can be introduced.

1. Test with hydrochloric acid, observing the action when cold and when heated. It must be remembered that some salts may be soluble only in dilute acid. Where the blowpipe-lamp is the only source of heat, the tube containing the acid and the mineral fragment or powder may be held in a tube-holder, and cautiously heated by blowing a smokeless blowpipe-flame (oxidising flame) beneath it. The tube-holder may be a mere band of folded paper twisted round the tube.

2. Insert the nozzle of the blowpipe two or three millimetres into the flame and blow fairly strongly, so as to oxidise as much of the glowing carbon particles as possible and thus provide a hot smokeless flame. The inner (reducing) region will now be almost colourless, and the hottest part of the flame lies just outside it. Hold a splinter of the substance in the platinum-pointed forceps or by platinum wire twisted round its upper portion, and heat in the hottest point of the flame.

Metallic substances, as ores of lead, antimony, and bismuth, that are likely to injure platinum must be heated on charcoal, or on a cleavage-rod of the infusible mineral kyanite. Observe against a dark background any *colouration imparted to the flame*. This colouration may be transitory, on entrance into the flame, or may become stronger during heating. Withdraw the splinter and examine for signs of *fusibility*. Then dip the splinter, first in hydrochloric acid, which may increase a characteristic colouration, or may produce a special one, as in the case of minerals containing copper; secondly, in sulphuric acid, which has a special effect in developing the greenish flame of phosphates. A double flame, as in calcium phosphate, may sometimes be noted.

Where potassium is suspected, the flame should be examined through blue glass set in a stand of convenient height. The blue glass usually supplied by dealers is far too thin, and lets through any bright flame, such as that due to sodium, which often appears pinkish. Use at least 5 mm. thickness of blue glass, which cuts off a strong sodium flame. A bright luminous flame will at any rate only give a blue effect with this thickness. Any pink flame due to potassium will then appear distinctly. The calcium and lithium flames are, moreover, not transmitted through this thickness of blue glass. When silicates are subjected to flame-tests, decomposition may be effected by melting the mineral particle in a bead of sodium carbonate, which is prepared beforehand by moistening a loop of platinum wire and picking up the salt upon it. The sodium carbonate is then fused, cooled, moistened, and the mineral fragment is picked up by its adhesion to the damp surface. It can then be fused into the bead, and if potassium is present, the pink flame becomes visible beyond the bead, the sodium flame showing merely as a blue trace.[1]

Where chlorine is suspected to occur in any quantity, a bead of microcosmic salt is prepared and a fragment of copper wire is melted up in it. The mineral is then added to the hot bead, and the bead is treated as if it were a splinter for examination. The chlorine volatilises as copper chloride, colouring the flame brilliantly blue beyond the bead.

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[1] G. Cole, "Flame-reaction of potassium in silicates," *Geol. Mag.* (1898), 103.

3. Observe the reactions in a *bead of borax*, after cooling from fusion (i) in the oxidising flame and (ii) in the reducing flame. The reducing flame is produced by holding the nozzle of the blowpipe just outside the lamp-flame and blowing somewhat gently. Sufficient air must, however, be imported into the flame to prevent a deposition of soot upon the surface of the bead. Where the opaque red reaction due to copper in the reducing flame is looked for, the colour is best seen by the yellow light of the lamp-flame.

4. Repeat the observations in a *bead of microcosmic salt* (hydrogen ammonium sodium phosphate). The bead is prepared by dipping the hot platinum loop into small quantities of the salt at a time and fusing thus successively, since a too large bead soon drops off the wire. Should this tendency be observed during an experiment, shift the bead at once to the upper part of the flame employed. The reactions in microcosmic salt are of especial service to the mineralogist as confirmations of those in borax. Cobalt often gives violet rather than blue beads. The copper reaction is more delicate and readily produced than in borax. The iron beads are both flesh-pink or brownish, while uranium gives green beads. These two elements are not distinguishable in borax. The yellow bead of tungsten and the violet of titanium in the reducing flame are highly characteristic.

A *silica residue* should be looked for in the microcosmic bead, remaining undissolved after prolonged heating. The slow solution of splinters of rutile and some few other minerals, and the possibility of an accidental admixture of quartz in many specimens, must be borne in mind.

5. Look for the evolution of water or the production of a sublimate in a dried *closed tube*. Where the mineral is likely to contain phosphorus, it should be fused in the closed tube with a little magnesium tape. If not easily fusible, it should be fused first on charcoal with sodium carbonate and the powdered slag should be inserted in the tube. After the tube has cooled, add a drop of water, and the characteristic smell

of hydrogen phosphide will be recognised if phosphorus is present.

6. Look for a sublimate or the evolution of a gaseous oxide in the *open tube*. Sulphur is often revealed here as SO_2.

7. Treat *on charcoal in the oxidising flame*. Observe any sublimate or change of the substance on oxidation. Metallic iodides may be produced on plaster of Paris plates by adding a mixture of 40 per cent. iodine and 60 per cent. sulphur.[1] The addition of von Kobell's mixture of potassium iodide and sulphur in equal parts to the substance treated serves to distinguish the lead sublimate from that of bismuth, lead iodide being more intensely yellow than the oxide, while bismuth iodide is a brilliant red.

If the sublimate or the substance is white after the oxidising flame has been employed, allow it to cool, add cobalt nitrate in solution, and reheat as strongly as possible in the oxidising flame. When cool, look for any colour imparted to the sublimate or the residue. A splinter of the mineral may often be conveniently treated with cobalt nitrate.

8. Treat the powdered mineral, with or without the addition of sodium carbonate, *on charcoal in the reducing flame*. Press out the residue on an anvil or in an agate mortar if metallic beads are not readily apparent. Even if no bead arises, test the powdered residue to see if it has become magnetic, iron, cobalt, or nickel being thus indicated. In such cases, test the material taken up by the bar magnet by treating it in beads of borax and microcosmic salt.

In all cases where metallic beads are found, rub the surface of the bead, which usually becomes oxidised as it cools, and flatten out the bead on an anvil to observe its properties. Tin, lead, and silver are easily distinguished by treatment of the bead on charcoal in the oxidising flame. Tin oxidises throughout to a white powder; lead becomes crusted over with orange oxide; both these beads give a streak of oxide beyond them on the charcoal. Silver may darken on cooling, but otherwise remains unchanged.

9. *Sulphur* is often present, as in sulphates, without giving

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[1] Wheeler and Luedeking, *Trans. St. Louis Acad. Sci.*, **4** (1886), 676.

any reaction in the preceding tests. The residue from thorough fusion in the reducing flame with sodium carbonate should therefore be dug out, with a little of the charcoal under it, which may have absorbed any sodium sulphide formed during the reduction. Crush out the mass with a drop of water on a clean silver coin, and the presence of sulphur is revealed by the decomposition of the sodium sulphide and a strong blackening of the silver by the sulphuretted hydrogen evolved. This reaction requires a grease-lamp and not a gas-flame, since the sulphur in gas is often sufficient to contaminate sodium carbonate on prolonged heating.

The details of blowpipe manipulation and reactions are given in text-books of practical chemistry. Reactions specially useful in determination will be mentioned under the head of the separate minerals in Part II. of the present work.[1]

Corrosion.

Mineral crystals are not unfrequently found which have suffered from corrosion or etching in natural solvents, and such attacks have proceeded on lines connected with the symmetry of the crystal-form. Just as dissimilar faces in a combination have probably always different hardnesses, so have they a difference of resistance to chemical attack. In a seemingly hexagonal form, alternate faces of a series may be more affected by etching than those between them, thus indicating the truly trigonal nature of the substance. The so-called pyramid in quartz is proved to consist of two rhombohedra, a positive and a negative, by the fact that one of these forms is more readily corroded than the other. The brighter series of three faces above and three alternating below is referred to the positive rhombohedron.

In calcite, the basal planes are much more easily corroded than the prism or rhombohedral faces.

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[1] A most complete and useful work for the mineralogist is by G. J. Brush and S. Penfield, "Manual of Determinative Mineralogy" (Wiley and Sons, New York), 16th Edition, 1905. See also for blowpipe reactions, G. Cole, "Aids in Practical Geology," 6th Edition, 1909, pp. 36-78.

In addition to this difference in resistance, the corrosion takes place by the excavation of little pits, the sides of which are crystal-faces near those of the one that is attacked, and the form of the corrosion-pits is regulated by the symmetry of the crystal structure. These *corrosion-figures* or " etch-figures " may be produced artificially, and have proved of immense service in indicating the true symmetry ot several species. In apatite, for example, the absence of vertical planes of symmetry is shown by their absence from the corrosion-figures produced on the planes of the vertical prism. The corrosion-figures on the cube-faces of rock-salt relegate the mineral to the low pentagonal icositetrahedral class. The relation of corrosion-figures to symmetry in all the classes is excellently shown in diagrams by H. A. Miers in his " Mineralogy " (1902), pp. 281–2.

PART II

THE DESCRIPTION OF MINERALS

CHAPTER IX

THE CLASSIFICATION OF MINERALS

OF all the characters of minerals, the chemical constitution appears to be the most fundamental, and it naturally takes an important position in any rational system of classification. When, however, we seek to group minerals according to their association in the field, we incline towards a scheme that shall bring together the ores of a particular element, rather than one that puts before us, say first the carbonates, then the phosphates, and then the sulphates, of diverse elements. Yet the crystallographer and the philosophic mineralogist find their most promising fields of research in comparing salts that have similar crystalline structure. An *economic classification*, which shows them the various salts of calcium at a glance, separates calcite from smithsonite and dialogite, and apatite from pyromorphite. The worker in natural history, on the other hand, will prefer the economic system. He visits a copper mine and collects seven or eight different ores of copper. If he can keep these together, his collection has a geographical as well as a chemical interest. A compromise that meets the views of various students may be found in arranging minerals by the important fundamental element in each, these elements being considered in the order of Mendeléef's table. By this means the ores of any one metal are kept together, while at the same time little violence is done to isomorphous groups. The silicates form so important a rock-forming group, and are often so complex in constitution, that they are best kept as a division by themselves. Inside this great division, if the whole range of the silicates is to be considered, the arrangement adopted in Dana's "System of Mineralogy" may be very conveniently followed, and the number assigned by Dana to a species may be marked on a small label attached to its representatives in the collection.

Similarly, within the subdivisions provided by the selection of fundamental elements, the various compounds may be arranged in the order of Dana's chemical groups. We thus have the following possibilities in each subdivision :—

Native Element.
Sulphides, tellurides, selenides, arsenides, antimonides.
Sulpharsenites, sulphantimonites, sulphobismuthites.
Chlorides, bromides, iodides, fluorides.
Oxides, including hydrous oxides.
Carbonates.

[Silicates; to be borne in mind here when of simple constitution, but to be discussed in the special Silicate group.]

Titanosilicates, titanates.
Niobates, tantalates.
Phosphates, arsenates, vanadates, antimonates.
Antimonites, arsenites.
Nitrates.
Borates, uranates.
Sulphates, chromates, tellurates.
Tellurites, selenites.
Tungstates, molybdates.
Salts of organic acids, as oxalates.

Whether a student begins his systematic observations with the silicates or not depends largely on the aim with which he approaches mineralogy. The geologist is naturally drawn towards the silicates, difficult though their study may prove to be, since they form so large a part of the rocks which he seeks to understand. The optical characters of minerals in thin slices are, moreover, illustrated to him mainly by silicates and by the one oxide quartz. The student of chemistry or mining will, however, enter most attractively on the mineral kingdom by a route that allows of blowpipe-analysis and a pleasing variety of chemical reactions. These reactions, indeed, make so general an appeal that a course which begins in the inverse order of Mendeléef's groups and ends with the silicates has been found of much practical advantage. The familiar iron subdivision thus appears at the outset, while gold and silver are reserved for later days. The miner can in the end make a broad survey of the silicates, and frequently treats them perfunctorily, with a kindly feeling towards kaolin and certain precious stones. The geologist, however, whose aim we are specially considering, reaches the silicates in the same course as a sort of climax. His more difficult work comes last, and the fact that by this time he is familiar with a variety of minerals that he has handled, and with specimens where crystalline form is readily apparent, will prevent him from regarding the earth as composed of bodies presented to his eye as thin sections under the microscope.

Marking out, then, Mendeléef's groups inversely, our minerals will be arranged as "ores" of the elements in the following order. The names of the more important elements used as the bases of subdivisions are printed in thick type.

Group.

8. **Iron**, **nickel**, **cobalt**, ruthenium, rhodium, palladium, osmium, **platinum**, iridium.
7. Fluorine, chlorine, **manganese**, bromine, iodine, samarium.
6. Oxygen, **sulphur**, **chromium**, selenium, molybdenum, tellurium, **tungsten**, **uranium**.
5. Nitrogen, **phosphorus**, vanadium, **arsenic**, niobium, **antimony**, tantalum, **bismuth**.
4. **Carbon**, **silicon**, **titanium**, germanium, zirconium, **tin**, cerium, **lead**, thorium.
3. Boron, **aluminium**, scandium, gallium, yttrium, indium, lanthanum, ytterbium, thallium.
2. Glucinum, **magnesium**, **calcium**, **zinc**, **strontium**, cadmium, **barium**, **mercury**, radium.

Group.

1. **Hydrogen**, lithium, **sodium**, **potassium**, **copper**, rubidium, **silver**, cæsium, **gold**.

0. Helium, neon, argon, krypton, xenon.[1]

SPECIAL DIVISION.—**Silicates.**

In the descriptions that follow, H. = hardness; G. = specific gravity. The Roman numeral after the name of a crystallographic system indicates the class. *Opt.* = optical characters. In the description of blowpipe-tests, O.F. means oxidising flame and R.F. reducing flame. The names of minerals of special geological interest or importance as ores are printed in thick type.

Figures representing refractive indices and other details are taken from various standard works, such as Lévy and Lacroix, "Tableaux des Minéraux des Roches," J. P. Iddings, "Rock Minerals," Miers, "Mineralogy," and J. D. Dana, "System of Mineralogy."

Such descriptions as are given here will, it is hoped, serve as aids in the examination of actual specimens, and, where rock-minerals are concerned, in the observation of their mode of association and occurrence in the masses of which they form a part.

With regard to the *nomenclature of minerals*, the advice of J. D. Dana, leading to the use of the termination "ite," has been widely followed in recent years. A subsidiary part, however, of Dana's scheme was the adoption of "yte" as a termination for the names of rocks, so that "granite" and "syenite" should not be regarded as mineral terms. So far from this proving a success, hundreds of rock-names have been promulgated which terminate in "ite," and hence it seems unnecessary to press for the general use of this syllable in forming mineral names. "Halite," moreover, is no great advance on the miner's term "Rock-Salt," and it is questionable if "Barite" is better than Barytes or "Uraninite" than Pitchblende. Even Dana preferred Pliny's Galena to his own

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[1] These elements, placed here by Mendeléef in 1904, are assigned positions in Group 8 according to their atomic weights by Tutton ("Crystalline Structure and Chemical Constitution," 1910, p. 12).

"Galenite," and Calamine was also left untouched. But the great number of names ending in "ine," with their pleasant reminiscences of French research, became in his great work terminated in "ite," and we have such curious forms as "Chalcocite" for Chalcosine, though not "Cuspidite" for Cuspidine. "Analcite" for Analcime is a useful correction; but the terminology of minerals formerly possessed, for the founders of the science, as agreeable a variety as that of other branches of natural history. There seems no need to make technical language harsh by the undue repetition of sounds that have no historic warrant.

CHAPTER X

GROUP VIII, INCLUDING IRON AND NICKEL

Iron.

Native Iron.—Though by no means common in the earth's crust, native iron is one of the most important constituents of the *meteorites* that fall from time to time upon the earth. Whatever theory we adopt as to the origin of the globe, there is high probability that meteorites give us a clue to the constitution of the unknown interior. The high density (5·5) of the earth as a whole, compared with the average density (2·65) of the rocks of the crust, suggests the presence of dense matter in the interior. A few meteorites reach us composed of basic silicates, with a specific gravity but little above 3. Others show scattered through them specks of metallic iron alloyed with a small percentage of nickel. Others have a ground of nickeliferous iron in which magnesium iron silicates, such as olivine, are embedded. A fourth group, including the largest cosmic masses known to us on the earth's surface, consist of metallic iron alloyed with various quantities of nickel, amounting often to about 7%. These iron meteorites possess a crystalline structure of crossing layers, which is revealed when a polished surface is etched with acid. The various alloys dissolve at different rates, disclosing what are known, after their discoverer,[1] as Widmanstätten figures.

The meteoric irons had been so well studied in conspicuous examples, that when A. E. Nordenskiöld, in 1870, reported the occurrence of similar masses embedded in the basalt of

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[1] Von Widmanstetter, also known as Widmanstätten, who observed them in 1808.

Uigfak, or Ovifak, Disko Island, W. Greenland, some critics felt that a meteorite must have fallen into the lava while it still lay molten on the surface. One of these Disko blocks measures six feet long, and weighs about nineteen tons. Later research has confirmed the view that the native iron is here a true constituent of the basalt, brought up with it from below, and specks of iron have been found in the basalt of the Giant's Causeway,[1] and a few other places. The Greenland iron contains about 93% of iron, and 2% of nickel, carbon being about as prominent as the nickel. On etching, it reveals Widmanstätten figures. In 1885, a ferriferous nickel was discovered in the South Island of New Zealand, and is known as *awaruite*. It occurs in river valleys as water-worn granules, probably washed from some mass of basic igneous rock; but it has not yet been traced up to its source. It contains Ni 68 and Fe 31%. Similar pebbles occur in Oregon and California, with Ni 76 and Fe 22%. E. S. Dana[2] points out that there thus appears to be a native terrestrial alloy with the composition Ni_3Fe. The probability of the occurrence of nickel-iron deep down in the earth, and reaching the surface only through eruptions of igneous magmas poor in silica and rich in magnesium and iron—the ultrabasic rocks of geologists—is thus largely increased. Suspicion even falls on the meteoric character of some iron masses resting on the earth's surface, such as the examples at Cañon Diablo, in Arizona, in which diamond has been found, and at Octibbeha, Mississippi, where the alloy contains Ni 40 and Fe 60%.

Tests.—A convenient test for small grains of metallic iron, separated with the magnet or lying in a rock-slice, is treatment with an acid solution of copper sulphate. Metallic copper is deposited in place of the exposed surface of iron, while magnetite, titaniferous iron ore, etc., remain unaffected.

Pyrite. FeS_2. Fe 46·7%.—Opaque; brass-yellow, streak black. H. = 6·5. G. = 5. Cubic II, pentagonal dodecahedral (Figs. 34 and 78). Common form the cube, with its faces often striated by repetitions of planes of the pentagonal dodecahedron; these striæ are perpendicular to one another on any adjacent pair of faces of the cube (Fig. 79). No cleavage, but a somewhat hackly fracture.

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[1] Andrews, Report British Association (1852), 34.

[2] "System of Mineralogy," Appendix II (1909), 11.

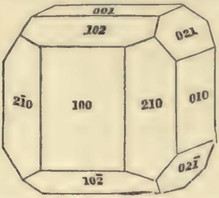

FIG. 78.—Crystal of pyrite, with cube and pentagonal dodecahedron.

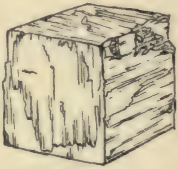

FIG. 79.—Pyrite (striated cube).

This extremely common mineral is the ordinary form of "Iron Pyrites," the other form being the rhombic type, marcasite. Pyrite as an ore is worked for its sulphur, and is largely used in the sulphuric acid trade.[1] Gold is occasionally extracted from it, and pyrite is often brought from long distances by inexperienced finders under the impression that it consists of gold. The brass-yellow cubes or pentagonal dodecahedra occur in slates near contact with igneous masses, and develop in argillaceous rocks without including the clay amid which they grow. The blue-black colour of many shales and clays is due to finely divided iron disulphide, as pyrite, or as its ally marcasite, and the rock weathers with a brown colour, owing to the formation of hydrated iron oxide. The two tints are often seen, one below the other, in brick-pits. In the Black Sea at the present day bacteria occur which destroy the sulphates that are in solution, and liberate hydrogen sulphide. This attacks the soluble iron salts, and the insoluble ferrous sulphide (FeS) is thrown down in the blackened mud of the sea-floor. The lower depths of the sea are, in such cases, practically poisoned for other forms of life. FeS may be converted into FeS_2 where hydrogen sulphide is abundant,[2] and in any case it does not appear to be a stable terrestrial mineral. We may presume that precipitated ferrous sulphide ultimately passes into the form of the disulphide. This is the probable mode of origin of some of the FeS_2 in clays of older date; but in many cases pyrite or marcasite is so intimately associated with molluscan and other animal remains, of which it forms moulds and casts, that its present position must be due to subsequent concentration. Pyrite often occurs in shales as concretionary masses, showing radial structure, but with knob-like representatives of cubes upon the surface (Fig. 80). All concretionary forms of FeS_2 are usually classed as marcasite in collections.

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[1] A good account of the uses of iron sulphides is given by A. Wilson, "Pyrites in Canada," *Canadian Department of Mines* (1912).

[2] Allen, etc., "The Mineral Sulphides of Iron," *Amer. Journ. Sci.*, **33** (1912), 191.

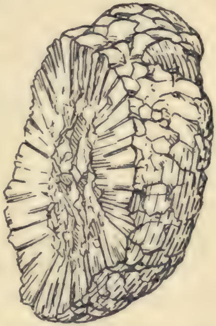

FIG. 80.—Concretionary pyrite.

On exposure to oxidising action, as on a rock-surface or in the soil, pyrite decomposes into ferrous sulphate, which poisons plant-life in the neighbourhood. All the iron is sometimes washed away as sulphate in solution, but more often a certain amount of iron-rust marks the former resting-place of the pyrite. At times the sulphur is oxidised away, and perfect pseudomorphs in limonite after the crystals of pyrite remain behind, preserving even the striation of the faces. Rocks containing frequent specks of pyrite are unsuitable for external decorative use.

Massive lodes of pyrite occur at times, and should be assayed for gold, while the far more valuable iron copper sulphide, copper pyrites, is often associated, and must not be overlooked.

Tests.—Insoluble in HCl. In the closed tube, gives a rich deposit of sulphur on heating. Brittle and not malleable. These tests and the hardness readily distinguish pyrite, even in small specimens, from gold. Copper pyrites is almost green-yellow in comparison, and is easily scratched with the knife.

Opt.—Opaque; the cubic form is often suggested by square sections under the microscope, which look brass-yellow, with a granular and scratched surface, when top-light is reflected from them.

Marcasite. FeS_2.—Opaque; has a yellow tarnish, but is tin-white when rubbed after cleaning with hydrochloric acid.[1] Rhombic I, "iron pyrites" being thus dimorphous. The crystals are bounded by sharp-edged domes, and are less common than radial concretionary forms or replacements and moulds of fossils in marcasite. Clustered crystals with curved faces give rise to aggregates known to miners as *cockscomb pyrites.* Marcasite is much more unstable than pyrite, and fossils and shales in collections often go to pieces, with the formation of filaments of iron sulphate, before the damage has been detected. The oxidation of the sulphide may develop so much heat as to ignite woody matter in exposed surfaces of rock, as in the cliff at Kimmeridge in Dorsetshire. Sulphur sometimes separates out. At 450° marcasite is slowly converted into pyrite with evolution of heat, and hence pyrite, and not marcasite, is the form found in igneous rocks.

Tests.—Stokes's test with HCl (see above) distinguishes concretionary forms from those of pyrite. Otherwise behaves like pyrite.

Pyrrhotine. Composition variable, but near Fe_7S_8.—Since the solubility of the mineral in HCl shows that FeS_2 is not present, the fundamental molecule is believed to be FeS, equivalent to the sulphide TROILITE, which is found in meteorites. The additional sulphur is regarded as a case of solid solution.[2] Opaque, bronze-yellow, tarnishing to brown. Hexagonal I, but usually merely massive. $H. = 4$. $G. = 4{\cdot}5$.

Pyrrhotine may contain 3 to 5 % of nickel, a fact of considerable interest when we regard the association of troilite with the nickel-iron of meteorites. The average amount of nickel in the pyrrhotine of Sudbury, Ontario, is 3·21%, largely in the form of included pentlandite (Ni, Fe)S.[3]

Tests.—Magnetic in various degrees, and sometimes attracts its own powder. Sulphur scarcely detected in closed tube. Soluble when boiled in HCl, with separation of sulphur. The lower hardness distinguishes it from pyrite and marcasite.

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[1] See Stokes, *U.S. Geol. Survey*, *Bull.* 186.

[2] Allen, Crenshaw, Johnston, and Larsen, "The Mineral Sulphides of Iron," *Amer. Journ. Sci.*, **33** (1912), 193.

[3] A. Coleman, *Rep. Bureau of Mines, Canada*, **14**, pt. 3 (1905), 158.

MISPICKEL. FeAsS.—Metallic white, tarnishing grey. Rhombic I; short prisms with angle near 70°. H. = 6. G. = 6. Used as a source of arsenic.

Tests.—The blowpipe-tests are easy, arsenic being detected in the tubes or on charcoal, as well as sulphur. The hardness is suggestive.

Hæmatite. Fe_2O_3, containing 70 % of iron.—Opaque except in thin flakes or sections, when it transmits a red light. Purple-red to black on surface; purple-red on fracture where powder has formed, the streak being a dull blood-red. From this the mineral gets its name (ἁίμα, blood). Crystals (*specular iron ore*) have a brilliant metallic lustre, the surface resembling a dark mirror. In these and the platy varieties (*micaceous hæmatite*) the red colour is only seen on crushing to a fine powder. Trigonal IV; rhombohedral combinations; but the edges of crystals are often rounded. Those from Elba are well known in collections. H.=6. G.=5, lower in some earthy varieties.

Hæmatite is not important as a rock-former, except in some bedded flinty rocks (*cherts*) and in the tropical earths and concretionary layers known as laterite, where it represents a dehydration in dry sunny conditions of hydrated products of decomposition. The hæmatite of certain red banded flinty rocks, as in the bedded series near Lake Superior,[1] has been claimed as a product of sedimentary deposition, through the action of oxygen upon sea-water locally charged with ferrous sulphate. $6FeSO_4 + 3O$ thus yields $2Fe_2(SO_4)_3 + Fe_2O_3$. In mineral veins hæmatite occurs in superb mammillated masses with a fibrous radial structure.

Opt.—Micaceous hæmatite occasionally appears in rock-slices, as translucent red plates. Opaque massive hæmatite shows the red streak on its ground surface by reflected light.

Ilmenite. $m\mathrm{FeTiO}_3 + n\mathrm{Fe}_2\mathrm{O}_3$.—Opaque black; decomposes to a dusky grey product, which is sometimes regarded as sphene, the lime being derived from adjacent calcium silicates.

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[1] Van Hise and Leith, "Geology of the Lake Superior Region," *U.S. Geol. Survey, Mon.* LII (1911), 516 and 527.

In rock-slices ilmenite appears metallic and black by reflected light (like magnetite) when fresh, but often shows whitish products in bands and patches. Translucent and brown in very thin sections. Trigonal; the forms are close to those of hæmatite. H. = 6. G. = 5. Ilmenite is common in granular forms in basic igneous rocks; but titaniferous magnetite may also occur. Black sands are occasionally found in rivers or on shores, which result from the concentration of ilmenite derived from the decay of basic rocks.

Tests.—Slowly soluble in HCl. The titanium may be detected as follows, by a combination of blowpipe and wet reactions. The first intimation occurs in the reduced bead of microcosmic salt, which is unusually dark and brown-red, in place of the pale tint due to iron alone. This may, however, indicate equally tungsten or titanium in the presence of iron. Powder the mineral with about three times its bulk of sodium carbonate and reduce thoroughly on charcoal; everything depends on the care given to the reduction. Then transfer the slaggy residue to a test-tube with water and HCl, inserting a piece of tinfoil about 2 cm. by 1 cm. Boil and allow to stand for half an hour. The titanium will be revealed by a pink-violet colouration of the liquid, owing to the formation of $TiCl_3$. The tin, by liberating hydrogen from the HCl, has provided a reducing atmosphere, in which the yellow colour due to ferric chloride cannot arise.

Magnetite. $Fe_3O_4(= Fe''Fe_2'''O_4)$. Fe 72·4%.—Some specimens are titaniferous. This is the typical member of a series of minerals known as *spinellids*, the family of the spinels, with the general symbol $RO . R_2O_3$, in which the Fe″ found in magnetite may be replaced by Mn, Zn, Cr″, or Mg, and the Fe‴ by Ti, Cr‴, or Al, until we reach the translucent gem spinel, $MgAl_2O_4$. Magnetite is black and opaque, even in thin slices, with an appearance as of filed iron when a section is viewed by light reflected from its surface. It is strikingly magnetic, attracting its own powder, and masses are sometimes polar, as may be seen when opposite points are turned to a compass needle.

The magnetic character is observable in the field, when the dust hammered from a vein flies back and encrusts the main mass with projecting fibres. This mineral is the *lodestone* of older writers, and occurs in some basic igneous rocks in such abundance as to prevent the use of compass-bearings by navigators. It takes its name from the promontory of Magnesia in the east of Thessaly, and from it "magnet" and "magnetism" have been derived.

Cubic I; typically as octahedra (Fig. 81). H. = 5·5. G. = 5. Occurs as the common iron ore in igneous rocks, crystallising out at an early stage during the cooling of the mass, and sometimes becoming segregated into huge bodies of ore within the igneous cauldron. Also as stratified beds, resulting from the reduction of other oxides, perhaps of bacterial origin (p. 179), or of iron carbonate, or even from direct precipitation.[1]

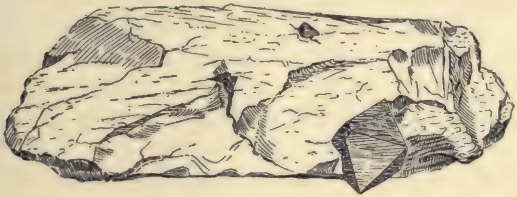

FIG. 81.—Magnetite in chlorite schist, Tyrol.

Tests.—Soluble in HCl. Fusibility 5. Is magnetic even before reduction on charcoal (the other iron oxides are reduced on charcoal to magnetite, and not to metallic iron, and can then be attracted by a magnet).

Opt.—In rock-slices is opaque, with iron-grey surface by reflected light. Granular, or square and hexagonal outlines, which arise from sections of octahedra.

CHROMITE (CHROME IRON ORE). $FeCr_2O_4$, but with Mg and perhaps Cr replacing part of the Fe, and Al and Fe part of the Cr.—A chromium spinellid. Black, like magnetite, but brown-red in very thin slices. Cubic I. H. = 5·5. G. = 4·5, less than that of magnetite.

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[1] Van Hise and Leith, *U.S. Geol. Survey, Mon.* LII., 527, who suggest the reaction $9FeSO_4 + 4O = 3Fe_2(SO_4)_3 + Fe_3O_4$.

This is the only commercial ore of chromium, and occurs as granules, larger segregations, and veins, in ultrabasic igneous rocks, as in the olivine-rocks of New Zealand and North Carolina, and in their altered representatives, the serpentines of Unst, in the Shetland Islands. Green films of nickel carbonate appear occasionally on the surface, showing interestingly the association of chromite with the deep-seated matter of the earth's crust.

Tests.—The four beads in borax and microcosmic salt are all green on cooling, the chromium masking the iron reactions. Magnetic after reduction on charcoal.

FRANKLINITE.—Though rare, occurring in abundance only at Franklin Furnace, New Jersey, this mineral is of interest as a zinc spinellid, R'' being here represented by Fe, Zn, and Mn, and R''' by Fe and Mn. Large octahedral crystals, like those of magnetite, occur.

Limonite. $Fe_4O_3(OH)_6$ or $2[Fe(OH)_3].Fe_2O_3(=2Fe_2O_3.3H_2O)$.—The common ferric hydrate or hydroxide in nature; the chemist is also acquainted with the normal hydroxide $Fe(OH)_3$, comparable with the aluminium mineral gibbsite; with $Fe_2O(OH)_4$, which appears to form the bulk of *bog iron ore;* and with $FeO(OH)$, which crystallises as göthite (see below). Limonite is orange-brown to brown, with yellow-brown streak (compare hæmatite). The crystalline form is unknown, though the frequency of fibrous concretionary types points to a crystalline tendency. It is possible that in actual crystallisation water is given off and göthite arises. H. = 5·5, but the mineral is sometimes powdery. G. = about 3·8.

Iron hydroxides (iron rusts) are responsible for almost all the brown tints known to the geologist. The colour of dry soil, of the surface of joints in granite or in basalt, of the whole groundwork in decomposing lavas, of many sandstones, and of the residues of limestone after solution in natural waters, is alike due to limonite or its allies. In mineral veins limonite occurs as concretionary layers and nodules, known as *brown hæmatite* by miners. The surface of masses of iron carbonate (siderite) is brown through ready oxidation. Where soluble salts of iron are exposed to oxidation, as when the surface of the water-table in the soil approaches the region where free permeation of rain-water and air takes place, an insoluble hydroxide is produced, and this cements the soil-particles and forms a gradually thickening "pan." In swamps, the presence of multitudes of iron-bacteria promote the deposition of iron hydroxide even in their own cell-walls. This was long ago noticed by Ehrenberg in the case of *Gaillonella* (*Gallionella*) *ferruginea*, and it is probable that the deposition results from the breaking up of ferrous carbonate, the carbon of which is required by the growing organisms.[1] Where decaying vegetation surrounds a pool, iron is leached out from the surrounding rocks and is supplied to the water in soluble combinations. The deposits of fresh-water lakes, whether sandstones or clays, become stained red-brown by the constant rain of iron hydroxides to the bottom as the unstable salts decompose. Organisms, as above remarked, assist in the process, and may build up spongy masses of bog iron ore, regarded as $Fe_2O(OH)_4$, where no other sediment is being formed. Such deposits are often concretionary, as in the lake-ores of Sweden, and the loose oolitic or pisolitic granules can be dredged up for commercial use.

Göthite. $FeO(OH)(=Fe_2O_3.H_2O)$.—Black-brown, with orange-yellow streak. Rhombic. Almost rectangular lustrous prisms. Axial ratio close to that of diaspore, $AlO(OH)$, and manganite, $MnO(OH)$. H. = 5·5. G. = 4. Often found with limonite.

Siderite (Chalybite). $FeCO_3$. Fe 48·27 %.—Colourless or grey, but almost invariably a pale yellow-brown, owing to oxidation (rusting) along the cleavage-planes. Trigonal IV; often as rhombohedra, with angles over polar edges 107°. Faces often curved, and the rhombohedra become sometimes actually lens-like. Cleavage rhombohedral, as in calcite. H. = 4. G. = 3·8. Concretionary forms of large size may occur in shales, their flatter directions lying along the bedding-planes. These are a great source of iron ore in the British coal-measures, and often include fossil remains. The "black band" ore of miners is a carbonaceous siderite. Siderite replaces some oolitic limestones, the structure of the rock and of the associated shells being perfectly preserved. The rock remains blue-grey in the interior, but is strongly brown on weathered surfaces. The iron ore of Jurassic age mined in the Cleveland Hills of Yorkshire is an example, and siderite in this and its other massive types is important as a rock-forming mineral.

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[1] See W. Benecke, "Bau und Leben der Bakterien" (1912), 487–498, and E. M. Mumford, "A new iron bacterium," *Trans. Chem. Soc.*, **103** (1913), 645.

Tests.—Dissolves with effervescence in hot HCl, colouring the liquid yellow. When touched with the blowpipe-flame, turns black and becomes magnetic (Fe_3O_4).

ILVAITE.—The calcium iron silicate $CaFe_2''(Fe'''OH)(SiO_4)_2$ is so essentially associated in Elba with the hæmatite iron ores that it may best be described here. SiO_2 about 30, Fe_2O_3 about 21, and FeO about 33 %. Rhombic, in black prismatic forms, weathering brown on exposed surfaces. H. = 5·5. G. = 4. In both these characters ilvaite resembles göthite, but it can be distinguished by forming a strong yellow jelly when boiled in HCl.

E. Weinschenk[1] has shown that the woolly fibres in cavities of a trachytic lava at Monte Olibano near Pozzuoli are capillary ilvaite, and not a pyroxene (breislakite), as was once supposed.

VIVIANITE. $Fe_3(PO_4)_2.8H_2O$.—Pale to deeper indigo-blue; sometimes as a dull blue powder. Glassy lustre and translucent when crystallised. Monoclinic, in flattened prismatic forms. Perfect cleavage (010). H. = 2. G. = 2·6. Of geological interest through its assocation with fossil bones to which ferruginous waters have had access, as in bogs. Also as a soil-constituent, the phosphorus becoming available for plant life when lime is introduced and calcium phosphate is in consequence built up.

COPPERAS (MELANTERITE). $FeSO_4.7H_2O$.—Greenish, Monoclinic; often fibrous. Soluble in water, with a characteristic inky taste. A common product of the decomposition of iron pyrites, especially of marcasite, but in nature passes off usually in solution.

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[1] *Zeitschr. für Krystallographie*, **37** (1903), 442.

Wolfram. (Fe,Mn)WO_4.—Deep brown to black. Submetallic lustre. Monoclinic, but very nearly rhombic in symmetry. Prismatic crystals, vertically striated. H. = 5·5. G. = 7·5. A common associate of tin ores. Attention is called to it by its weight, which distinguishes it at once from some dark silicates. Valuable as a source of tungsten. Hübnerite ($MnWO_4$) is lighter in colour.

Tests.—The high specific gravity is at once suggestive. The bead of microcosmic salt in the reducing flame is crimson-red. When thoroughly reduced with sodium carbonate and treated as is described under ilmenite, the liquid turns dull blue and ultimately brown on standing, indicating tungsten. The manganese may be found by forming a sodium carbonate bead on platinum wire, moistening it to cause the mineral powder to adhere, and heating in the oxidising flame. The characteristic green colour is imparted to the opaque bead.

The iron is found by picking out magnetic particles after the mineral is reduced on charcoal, and testing these in borax.

Nickel.

NATIVE NICKEL. See under native iron.

MILLERITE. NiS.—Gold-yellow metallic prisms and hair-like fibres in the cavities of nickeliferous veins.

PENTLANDITE. (Fe,Ni)S.—Ni about 34 %, Fe 30 %, and S 35 %. Brass-yellow; metallic lustre. Cubic, with octahedral cleavage. Not magnetic. Embedded in pyrrhotine, forms the valuable nickel ore at Sudbury, Ontario.[1]

Nickeline (Kupfernickel).[2] NiAs. Ni 43·9 %.—Metallic copper-red. Hexagonal, but commonly massive. H. = 5·5. G. = 7·5. A common and handsome ore of nickel, conspicuous by its specific gravity.

Tests.—Furnishes a magnetic globule (Ni) after fusion on charcoal. The microcosmic salt bead must be treated on charcoal and not on platinum wire, owing to the arsenic, which fuses with the platinum; it gives in the reducing flame the characteristic yellow colour due to nickel. If this is complicated by the presence of cobalt, a borax bead must be made and the cobalt dissolved out in this, the blue glass being broken away and new borax being added until a brownish residue remains. This residual material fused in the reducing flame in microcosmic salt will give the yellow reaction of nickel.

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[1] Coleman, "Nickel Industry," *Canadian Depart. Mines* (1913).

[2] Dana writes "Niccolite," which fails to recall the interesting old mining term Kupfernickel, whence the element nickel gets its name. Nickel, a German goblin, was held responsible for these ores, just as the generalised Kobold was supposed to annoy miners with stores of unprofitable cobalt.

BREITHAUPTITE (NiSb) is similar in appearance and is isomorphous, but is much rarer.

CHLOANTHITE. (Ni, Co, Fe) As_2.—Tin-white. Cubic; {111} and {100}. H. = 5·5. G. = 6·4 — 7. This is the nickeliferous end of a series, with Ni about 20%, which terminates in smaltine, where cobalt is predominant over nickel.

Tests.—The blowpipe tests must be carried out as given above under nickeline. Distinguished from the similarly metallic white mineral mispickel by higher specific gravity and the absence of sulphur.

ZARATITE (EMERALD NICKEL). $Ni_3CO_5.6H_2O$.—The bright green crusts of this mineral often call attention to the occurrence of nickel ores, as on the surface of the magnetite of Galicia in Spain, which contains millerite.

GARNIERITE.—An important green nickel magnesium silicate. See Silicates, Serpentine division.

Cobalt.

The element takes its name from the Kobold, the mine-goblin, who placed its ores underground in order to annoy seekers after copper or more valuable materials.

COBALTINE. CoAsS.—Metallic white with a pale pink flush, noticeable at once when the mineral is placed beside smaltine. Cubic II; pentagonal dodecahedron, and combinations resembling those of pyrite. Cleavage cubic. H. = 5·5. G. = 6.

Tests.—The sulphur does not appear in the closed tube, but is easily found by the wet test after fusion on charcoal. The other reactions are obvious, the beads of the fluxes being prepared on charcoal.

Smaltine. $(Co,Fe,Ni)As_2$.—Like chloanthite, but with cobalt predominant over nickel.

ASBOLAN.—A black cobalt oxide found in "bog manganese," sometimes up to 30 % of the whole.

ERYTHRINE (Cobalt Bloom). $Co_3(AsO_4)_2.8H_2O$.—Compare the molecular structure of vivianite, with which erythrine is nearly isomorphous. Forms pink crusts, indicating the presence of other cobalt ores.

Platinum.

Native Platinum.—Usually alloyed with iridium, osmium, iron, etc., having a specific gravity of 14 to 19, as against that of refined platinum, 21. Mostly occurs in scales and small nuggets in alluvial deposits. In the Urals, in Borneo, and in New Zealand it appears to be concentrated in river-beds from ultrabasic igneous rocks, such as serpentine; and it at once assumes a geological importance as representing one of the dense materials of the earth's interior, which is rarely brought up to the surface. In British Columbia[1] platinum nuggets include chromite, olivine, serpentine, mica, and pyroxene, affording clear evidence of their petrographic relationships.

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[1] Kemp, *U.S. Geol. Survey*, *Bulletin* 193 (1902).

CHAPTER XI

GROUPS VII, VI, AND V, INCLUDING MANGANESE, URANIUM, AND ANTIMONY

GROUP VII.

Manganese.

WHERE iron salts oxidise and rust, yielding brown colouring matter, oxides of manganese are often at the same time formed; and the black films on rocks or in crevices are commonly due to manganite, psilomelane, or wad. Bacterial action deposits manganese hydroxide, corresponding to bog iron ore, and sometimes concentrates the manganese from waters which are actually more rich in iron. Delicate dendritic forms are often seen in chalk, spreading out from some small concretion along cracks in the rock, and resembling minute branching seaweeds. The common ores are the dark-coloured oxides.

ALABANDINE.—A rare sulphide (MnS); iron-grey with a grey-green streak. Cubic.

POLIANITE. MnO_2 ($= MnMnO_4$).—Iron-grey, streak black. Tetragonal I, and interestingly isomorphous with zircon ($ZrSiO_4$), rutile, and cassiterite. Long confused with pyrolusite, though recognised by Breithaupt in 1832. H. = 6—6·5. G. = 5. The hardness is its most striking character. It is sometimes pseudomorphous after manganite.

Pyrolusite. MnO_2.—Black, with a low lustre. Rhombic, but possibly pseudomorphous after manganite, its forms being similar. H. = 2—2·5. G. = 4·8. Arises sometimes as a dehydrated product of manganite, and may at other times result from a molecular rearrangement of the material of polianite. Largely mined as an ore.

Tests.—Soils the fingers. Usually a little water, probably from residual manganite, is given off in the closed tube. Excellent manganese reactions in the beads of the fluxes, but occasionally disturbed by the presence of iron.

HAUSMANNITE. Mn_3O_4.—Brown-black, streak brown. Tetragonal; bipyramidal forms; $a : c = 1 : 1{\cdot}1743$. H. = 5—5·5.

Manganite. $MnO(OH)$ ($= Mn_2O_3 . H_2O$).—Black; streak shows a trace of brown. Less brilliantly lustrous than göthite, which it resembles in its rhombic prismatic forms. H. = 4. G. = 4·3. The black dendritic markings in rocks are commonly ascribed to manganite.

Tests.—Harder than pyrolusite. The water in the closed tube is not a sure distinction.

Psilomelane.—The discovery of a crystalline form, styled *Hollandite*, in 1906,[1] decides the formula as $(H_4,K_4,Ba_2)(Mn,Fe)O_5$, the corresponding acid being H_4MnO_5. Black, almost dull. H. = 5—6. G. about 4. Forms crusts and stalactitic or mammillated masses in veins, often of considerable size. A common ore of manganese.

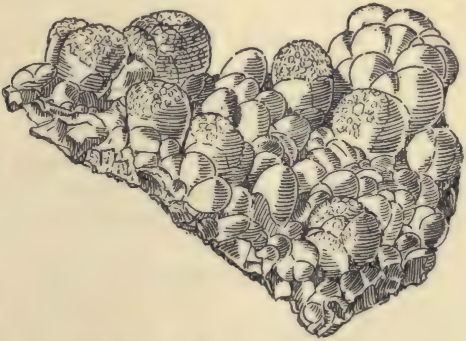

FIG. 82.—Psilomelane, Thuringia.

Tests.—When dissolved in HCl, liberates chlorine; the addition of H_2SO_4 precipitates the barium as a sulphate.

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[1] Fermor, *Rec. Geol. Surv. India*, **36** (1908), 295.

Barium may sometimes be detected in the flame by a momentary green flash.

Wad (Bog Manganese).—Hydrous oxide of Mn, Ba, Fe; possibly a form of psilomelane in an earthy state. The variable hardness reminds one of the contrast between the powdery and massive types of bog iron ore, of which wad is the manganiferous representative. Black. G. = 4. Typically a swamp deposit, as in New York State, and no doubt largely aided by bacterial action. *Asbolan* is a cobaltiferous wad, and has been referred to among cobalt ores.

BRAUNITE. Mn_2O_3 with $MnSiO_3$, the silica being now regarded as an essential feature.—Dark brown to grey. Tetragonal; the bipyramids are nearly octahedra, *c* being 0·9853 (compare Hausmannite). H. = 6·5. G. = 4·8. A fairly common ore.

Tests.—In HCl yields a silica jelly, with evolution of Cl.

DIALOGITE (RHODOCROSITE). $MnCO_3$.—Pale pink to pink-brown. Translucent in good crystals, with vitreous lustre. Trigonal IV; one of the series of rhombohedral carbonates; common form the rhombohedron, angle over polar edges 107°. Cleavage rhombohedral, perfect. H. = 4. G. = 3·5. Dialogite may indicate near the surface the presence of manganese ores below, and its colour attracts attention, since pink calcite, which it resembles, is very rare. May be responsible for the pink tints in certain ferruginous sandstones.

Tests.—Dissolves with effervescence in hot HCl. Mn reactions in the beads.

RHODONITE. $MnSiO_3$.—This silicate will be dealt with among the pyroxenes, of which it is an interesting triclinic member; but it should be borne in mind here, since it is pink, like dialogite, and often effervesces in hot acid, through the formation of some carbonate on exposure. *Fowlerite*, (Mn, Zn) SiO_3, is also pink, and in its large well-formed crystals might be mistaken for a felspar.

HÜBNERITE. $MnWO_4$.—Brown; lighter in colour than wolfram, with which it is isomorphous.

GROUP VI.

Sulphur.

Native Sulphur.—Pale yellow; brown-orange when selenium is present (*Selensulphur*). Resinous lustre; looks like gum on fracture. Translucent to nearly opaque. Rhombic I; $a:b:c = 0{\cdot}813:1:1{\cdot}903$. Common forms somewhat tall bipyramids and bipyramidal combinations (Fig. 18). On fusion, cools in monoclinic prisms, which ultimately break up into the stable rhombic form, as found in nature. Conchoidal fracture. H. = 2. G. = 2. Occurs in clays, and near volcanic vapour-jets and hot springs. In volcanic passages it probably results from the reaction of the gases hydrogen sulphide and sulphide dioxide on one another. The former gas is common in the later stages of volcanic activity, and part of it burns as it nears the surface, water arising at the same time—

$$H_2S + 3O = H_2O + SO_2$$

By interaction with further hydrogen sulphide, we have

$$2H_2S + SO_2 = 2H_2O + 3S$$ [1]

Especially fine crystals have been deposited at Cianciana, north-west of Girgenti in Sicily, associated with celestine and aragonite. The Sicilian sulphur-bearing strata are gypsiferous marls of Upper Miocene age, and a lagoon origin is thus suggested. Volcanic vapours may, however, have been prevalent, and the beds of the same age on the north-east of the Apennines, which contain sulphur from near Forli to Fabriano, are associated with mountain-building movements, and with the opening of Italian vulcanicity.[2]

The geysers of California and New Zealand deposit sulphur, and certain bacteria accumulate minute globules of sulphur in their cells. Stanislas Meunier[3] has described a case where decaying plants and other organisms caused the production of nodules of sulphur in an old swamp-deposit under Paris, through the reduction of calcium sulphate. This salt had reached the swamp in solution from accumulations of plaster thrown into adjacent ditches in the seventeenth century.

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[1] Newth, "Inorganic Chemistry" (1909), 309.

[2] For numerous useful references and maps see O. Stutzer, "Die Nicht-Erze," Teil i (1911), 197.

[3] *Comptes rendus* (1902), 915.

Tests.—Easily fusible. Burns in air, producing sulphur dioxide.

Chromium.

Chromite. $(Fe'',Mg)(Cr,Fe''',Al)_2O_4$.—See Iron series.

Molybdenum.

MOLYBDENITE. MoS_2.—Metallic grey, opaque. Gives a greenish-grey streak on paper. Hexagonal, but crystals have rounded edges, even in the case of the fine examples from Refrew Co., Ontario. Flaky, owing to basal cleavage. H. = 1–1·5. G. = 4·5. Occurs diffused as an original constituent of many granitoid rocks, as in Co. Donegal, resembling galena at first sight. Is sought after for use in steel-manufacture, and repays picking from the broken rock when the flakes or crystals are sufficiently large.

Tests.—Is not so black as graphite, and is more metallic in aspect. In powder blows away before the blowpipe; but a lump, larger than that usually selected in blowpipe-work, gives a good deposit of white MoO_3 on charcoal in the oxidising flame. When touched for an instant with the reducing flame, this oxide becomes a rich Prussian blue. Gives a flame (Mo) resembling that of barium. The borax head in O.F. is colourless, in R.F. brown. In microcosmic salt both beads are green. These are characteristic molydenum reactions, and platinum wire may be safely used.

See also WULFENITE in the Lead series.

Tungsten.

One of the most effective tests for tungsten is in microcosmic salt, where the bead is colourless in O.F. and a clear blue in R.F., not so dark or approaching violet as that given by cobalt. The R.F. bead is deep red if iron is present. The test given under Wolfram, where a dull blue solution arises, is the most satisfactory. Charcoal must be used that is free from any contamination with cobalt nitrate.

The ores of tungsten are treated in this book as the tungstates of iron and manganese (WOLFRAM), of lime (SCHEELITE, $CaWO_4$), and of lead (STOLZITE, $PbWO_4$).

Uranium.

Compounds of uranium have increased enormously in interest and in value since the discovery of radium as their natural associate (see Radioactivity, p. 148, and P. Krusch, "Ueber die nutzbaren Radiumlagerstätten," *Comptes rendus*, 11me Congrès géol. internat., 1912, p. 1165). Prior to this, the commercial use of uranium was as a yellow colouring for porcelain enamels. The beads of the fluxes are good tests, giving in borax O.F. yellow, R.F. bottle-green (like iron), but in microcosmic salt green in both flames. It will be borne in mind that the beads of iron minerals in microcosmic salt are flesh-red, while with chromium all four beads are green, and with molybdenum the borax beads are O.F. colourless, R.F. brown.

COPPER URANITE (TORBERNITE). $Cu(UO_2)_2(PO_4)_2.8H_2O$. —This may be taken as the type of a series of phosphates and arsenates of uranium and some other metal. The yellow mineral AUTUNITE is thus $Ca(UO_2)_2(PO_4)_2.8H_2O$. Copper Uranite is bright green and flaky, like a mica; but its basal cleavage-laminæ are not flexible. Tetragonal, in platy crystals, with broad basal planes. H. = 2–2·5. G. = 3·5. Common in tin-bearing areas, where its colour renders it conspicuous.

Pitchblende (Uraninite).—An association of oxides, mainly UO_2 and UO_3, but with protoxides of Pb, Fe, Ca, Zn, Mg, Mn, Cu. Th, Ce, Y, La, and Di may be present. Some silica is always present. Radium ore occurs as streaks in the massive mineral, as was discovered by Mde. Curie in 1903, and the presence of lead is of especial significance as a probable product of successive transformations in the uranium-radium series. Pitch-black, resinous lustre, opaque. Cubic, but commonly massive, with conchoidal fracture. H. = 5·5. G. = about 7, and may be as high as 8.

Occurs with silver and lead ores at Přibram, in Bohemia, and in tin and copper areas in Cornwall. Sir W. Ramsay procured helium and argon from a pitchblende with thorium, cerium, and yttrium, known as *Cleveite*, in 1897. Pitchblende is the commercial ore from which radium, in the form of bromide, is extracted.

Tests.—See those given under Uranium above. The specific gravity at once attracts attention.

SAMARSKITE, a uranium yttrium cerium erbium niobate, may serve as a type of a very interesting series of minerals with a black pitchy appearance, H. about 6, and G. about 6, which are indistinguishable except on analysis, and which possess special importance in radioactive research.

GROUP V.

Phosphorus.

The minerals in which phosphorus is an important constituent appear as phosphates of various metals. The grey-green flame due to phosphorus is seen in most of them, especially on treatment of the mineral splinter with sulphuric acid, and they respond to the wet test, giving, like arsenates, a yellow precipitate with ammonium molybdate dissolved in nitric acid. The test with magnesium tape, described under closed tube reactions on p. 161, serves for the detection of phosphorus in obscure cases.

Arsenic.

Native Arsenic.—Trigonal IV. Usually massive. Tin-white to dark grey. H. = 3·5. G. = 6. A common ore in veins.

REALGAR. AsS.—Orange-red, streak orange. Resinous lustre. Translucent. Monoclinic, and commonly crystallised. H. = 1·5—2. G. = 3·5. Its colour makes it conspicuous in veins; occurs sometimes as a product of the later phases of volcanic action.

ORPIMENT. As_2S_3.—Yellow (the *auripigmentum*, "colour of gold," of old writers); streak yellow. Resinous lustre. Monoclinic. Perfect clinopinacoidal cleavage, yielding large flaky specimens. H. = 1·5—2. G. = 3·5. Occurs in very various rocks, from clays to lavas, and is one of the most brilliantly coloured minerals.

Mispickel, the main commercial source of arsenic, is dealt with under Iron.

ARSENOLITE. As_2O_3.—White and soluble in water. Cubic. This is the form in which arsenic passes into certain springs.

Antimony.

NATIVE ANTIMONY.—Tin-white. Trigonal IV. Rhombohedral and other angles close to those of arsenic. Brittle. H. = 3—3·5. G. = 6·7, somewhat higher than that of arsenic.

Stibnite (Antimonite). Sb_2S_3. — Metallic lead-grey. Rhombic I. Crystals prismatic, and striated vertically. Radial and fibrous bundles frequent. H. = 2. G. = 4·5. Fusibility = 1. This handsome ore supplies practically all the antimony of commerce.

Tests.—Sublimes as a whole in the closed tube, becoming re-deposited as a dark brown-red sublimate. White oxide and odour of SO_2 in open tube. Greenish antimony flame-reaction.

KERMESITE. Sb_2S_2O.—Pink-red radiating fibrous crystals. Monoclinic. An alteration-product of stibnite.

VALENTINITE, occurring in stellar groups of white rhombic crystals, and SENARMONTITE, crystallising in white octahedra, are dimorphous forms of Sb_2O_3.

Tantalum.

COLUMBITE. $(Fe,Mn)(Nb,Ta)_2O_4$. — Usually contains some tin. Black. Rhombic I; stout prisms with {100} and {010}, producing a squarish cross-section. H. = 6. G. about

6. Occurs in granitoid rocks, and is the chief source of tantalum for the metallic filaments of electric lamps.

TANTALITE. $(Fe,Mn)Ta_2O_6$.—Usually contains some tin. Black. Rhombic I; nearly resembling columbite, but with higher specific gravity (about 7·5). Occurs like columbite, and is similarly used.

Bismuth.

The yellow oxide of bismuth that is formed on charcoal passes outward into white, and is paler than that of lead. If a mixture of equal parts of potassium iodide and sulphur is added to the substance that is being tested, a brilliant vermilion sublimate of bismuth iodide is formed. The metallic bead is somewhat brittle and does not mark paper.

Native Bismuth.—Silver-white, tarnishing yellowish. Trigonal IV, the rhombohedra nearly resembling cubes. Brittle. H. = 2—2·5. G. = 9·7. Fuses easily and volatilises. Occurs as the common ore of bismuth in considerable veins, with silver and lead ores.

Tests.—As above. The specific gravity is exceptionally high.

BISMUTHINE. Bi_2S_3.—Lead-grey to tin-white, tarnishing yellowish. Rhombic; in narrow prisms, resembling stibnite. H. = 2. G. = 6·5. Fusibility = 1.

CHAPTER XII

GROUP IV, INCLUDING CARBON, SILICON, TIN, AND LEAD

Carbon.

Diamond. C.—Colourless and transparent; sometimes yellowish, and rarely blue, pink, or even black. Adamantine lustre. Cubic III; but octahedra and hexakis-octahedra are common, while forms of the tetrahedral series are comparatively rare (Fig. 83). Perfect octahedral cleavage; advantage is taken of this by gem-cutters. H. = 10. G. = 3·5.

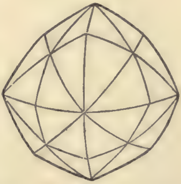

FIG. 83.—Hexakis-octahedral diamond, with characteristically curved faces.

The hardness, lustre, and high refractive index of diamond have made it greatly prized as a gem, the value increasing enormously with size. Until January, 1905, the largest known diamond was the lost "Great Mogul," an Indian stone seen by Tavernier in 1665. This weighed 787 carats, the uncut stone having been about 1000 carats. The carat is 3·1683 grains Troy (0·205 gramme), and the Great Mogul diamond thus weighed about half a pound avoirdupois. In 1905, a fragment of a giant diamond was found at the Premier Mine near Pretoria, Transvaal, which was cut into nine large and ninety-six smaller pieces in 1908, after presentation to the British Crown. This, known as the "Cullinan" diamond, measured 4 × 2½ × 2 inches, and weighed 3025¾ carats (621·2 grammes),[1] or one and a third pounds avoirdupois

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[1] F. H. Hatch, *Geol. Mag.* (1905), 170; L. J. Spencer, *Min. Mag.*, **15** (1910), 322. See also Spencer, "The Larger Diamonds of South Africa," *ibid.*, **16** (1911), 140.

(Fig. 84). South Africa had previously yielded from Jagersfontein the "Excelsior" diamond, three inches in diameter, and weighing 971 carats. This was cut into nine gems. The noblest mineral specimens of diamond are always liable to be thus lost to science, owing to the impossibility of their being utilised as single ornamental stones.

Opt.—Isotropic between crossed nicols, which distinguishes diamond from topaz or quartz, but not from glass or spinel.

The refractive index in air, 2·42, is little short of that of rutile; hence the cut gem has great reflective power, a back plane returning by total reflection all rays that strike it at a greater angle from the normal than $24° 25'$ (see p. 97).

The great diamonds of India were found in alluvial deposits at Golconda, in Haidarabad, a locality now practically worked out. In Brazil they occur in sandstone; but few geologists regard these rocks as their place of origin. From 1871 onwards, the most active diamond mining has been carried on in the necks of old volcanoes at Kimberley, a town now included in the Cape Province, and at other places in S. Africa. The matrix is a fragmental ultrabasic igneous rock (serpentine), with abundant green pyroxene and red garnet; the two latter minerals are often associated together as fragments of the rock called eclogite, and T. G. Bonney, in 1899, found diamond in a block of this eclogite from a volcanic pipe in the Orange Free State. Hence the probable ground in which the carbon crystallised is this old metamorphic rock, through which the explosions have bored their way, bringing up olivine-rocks, now converted into serpentines, from below.

Carbon occurs commonly in meteorites, and diamond has been found in the iron meteorites of Cañon Diablo, Arizona (see p. 171), of Novo-Urei in Russia, and Carcote in Chile. Diamond has been artificially crystallised in castings of molten iron, owing to the pressure produced by the expansion of the iron at the moment of solidification. Hence there is good reason to believe that diamonds may be common, and of large size, in the earth's interior, though they are rarely brought up to the surface. There is no necessity for referring terrestrial forms of carbon to reduction from some organic source, since

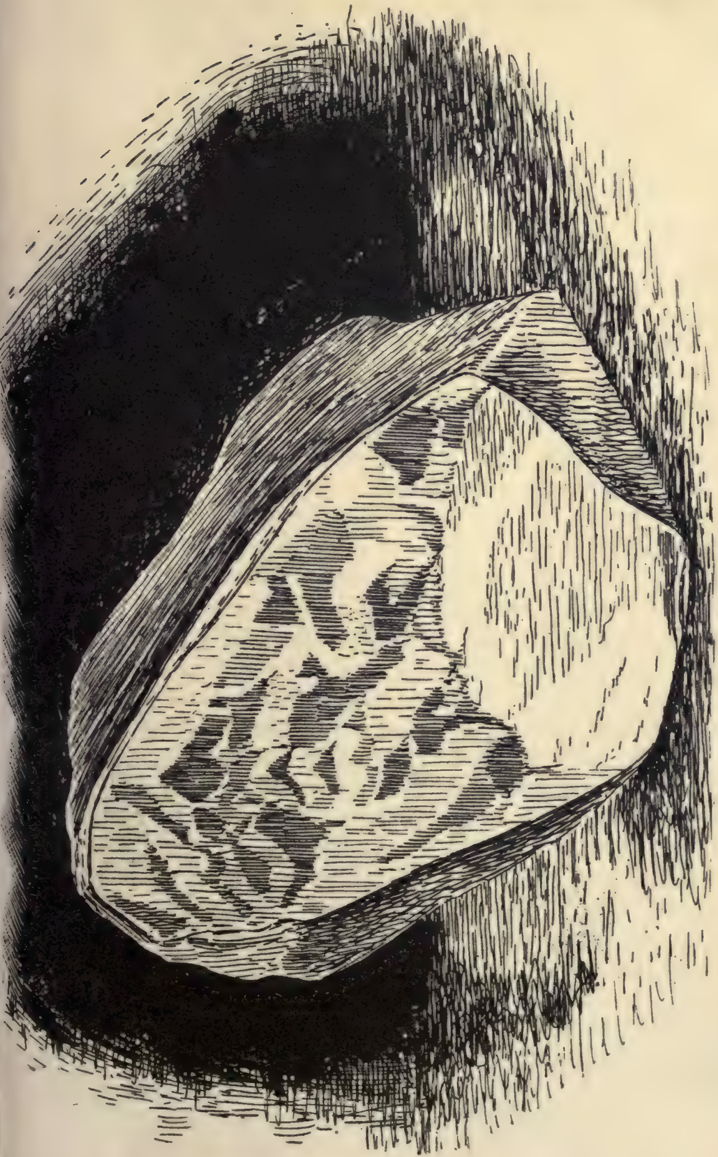

FIG. 84.—The Cullinan diamond, actual size.
(*From a model by Krantz of Bonn.*)

all the carbon utilised by organisms must have been at one time in an inorganic form, while carbon dioxide permeates many granitic rocks as a liquid, and is, as a gas, a prominent constituent of springs in all volcanic areas.

Carbonado or *Bort* is a black massive form of diamond found in the Province of Bahia in Brazil; it is granular and sometimes spongy in texture. A mass found about 1895 weighed 631·9 grammes, or more than the Cullinan diamond. This material is used for setting in the crowns of diamond drills, since it is tough as well as hard, having no continuous cleavage.

Graphite (Plumbago; Black Lead). C.—Black, opaque, with an almost metallic lustre. Trigonal IV, but commonly massive, with a scaly structure due to its perfect basal cleavage. Carbon is thus dimorphous. H. = 1—2; feels greasy and marks paper, its streak being known to all users of "black lead" pencils. G. = 2—2·2.

Graphite occurs at times in beds, which may even retain the structure of fossil vegetation, and it thus shows itself to be a final product of the processes which change wood to coal, and which usually terminate in anthracite. But at Borrowdale in Cumberland graphite is found in the cavities of volcanic lavas, and in Bohemia and elsewhere it forms great masses, like bodies of ore, in highly metamorphosed rocks which seem in part of igneous origin. In North America graphite has been cited as evidence of the occurrence of vegetation in the pre-Cambrian era, since it occurs associated with altered limestones and with schists and gneisses. But the remarks made above as to diamond must here be borne in mind, and masses of carbon may exist in the earth's interior which have not yet played any part in the structure of organisms.[1]

Tests.—Blacker than molybdenite. When strongly heated in air, glows and is turned very slowly into carbon dioxide gas.

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[1] While F. Kretschmer (abstract in *Geol. Centralblatt*, **3**, 514) sees organic features in all graphites, E. Weinschenk strongly opposes this contention (*C. R.*, *VIII. Congrès Géol. Internat.*, 1901, 447).

Silicon.

A large part of the silicon of the earth's crust is locked up in silicates. The dioxide SiO_2 forms, however, one of the commonest minerals, and is at least trimorphous.

Quartz (Rock-Crystal). SiO_2. — Commonly colourless; coloured varieties have received various names. Typically transparent, with a fine vitreous lustre. Trigonal VI, the trapezohedron appearing less commonly than the second order trigonal bipyramid. When the latter is also absent, the forms appear to belong to Class I of the hexagonal system, and they are often popularly so described. Common form hexagonal prism of first order capped by hexagonal bipyramid of the same order, the latter being formed by combination of the positive and negative rhombohedra. Angle over any of the six polar edges $(10\bar{1}1)$ $(01\bar{1}1)$, 133° 44′; between the rhombohedron-plane and the prism-plane below it, 141° 47′. The prism varies in length, and is usually long in proportion in crystals formed from solution, as in veins or in the microscopic crystals developed in limestone. It is short in the quartz arising in igneous rocks, as in quartz-porphyries; this quartz may possibly be hexagonal (see below). Through repetition of rhombohedron-faces, the prism-planes are very commonly striated perpendicularly to the direction of the *c*-axis (Fig. 87). Occasionally one rhombohedron alone occurs, or is more conspicuously developed than the other. The six planes of one of them, three at each end of the crystal, may be brighter than those alternating with them (p. 163), and these are selected as the positive form. By complete interpenetrant twinning of two crystals with their axes parallel, with (0001) as the twin-plane, and the *c*-axis as the twin-axis, each of the twelve rhombohedral faces is composed in part of a plane from the positive form of one crystal, and in part of a plane from the negative form of the other crystal. Hence natural or artificial corrosion divides the face into two parts, a brighter and a duller, meeting along an irregular line, and the bright part of one face is found to correspond exactly with the dull part of the adjacent face, as we trace it over the polar edge. The interlocking of the two forms can thus be read off (Fig. 85). The basal plane is extremely rare. Among the most common additional planes are those of the second order trigonal bipyramid $\{11\bar{2}1\}$, occurring as small rhombs on six of the solid angles formed by the union of the rhombohedra and the prism; that is, on three alternating angles above and on the three vertically below them. Sometimes, and still more interestingly, the planes of the trigonal trapezohedron $\{51\bar{6}1\}$ or $\{6\bar{1}\bar{5}1\}$ also occur, deciding the symmetry of the form, and set skew-wise on the same angles (Fig. 86) as those that receive the trigonal pyramid planes. If these planes occur at the right-hand top corner of the prism-plane when the crystal is held upright, the form is right-handed; if at the left-hand top corner, it is left-handed.

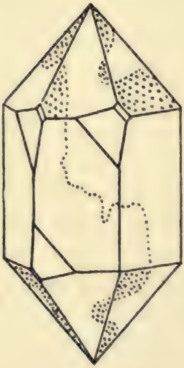
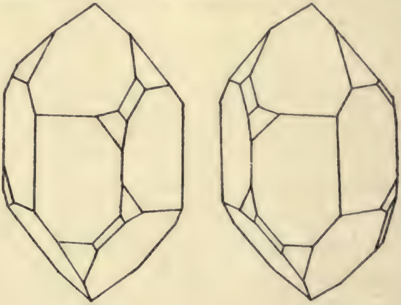


FIG. 85. — Interpenetrant twin of two right-handed crystals of quartz, showing corrosion of the negative rhombohedral planes. (After Groth.)



(i) (ii)

FIG. 86.—(i) Right-handed, and (ii) left-handed crystal of quartz. (After Groth.)

Various types of twins occur; but twinning is not seen in the common rock-forming crystals in thin slices. *Conchoidal fracture*, but no cleavage, a very important character, since so many other hard colourless minerals in rocks display smooth cleavage-surfaces. H. = 7. G. = 2·65.

Rock-forming quartz is almost always colourless, or white through minute inclusions (*milky quartz*). *Amethyst* is a purple variety, the colour being irregularly distributed in the crystal. *Smoky quartz* is dusky brown to black, giving a purplish tint to transmitted light; fine crystals are occasionally found in veins. Yellow varieties are known as *Citrine* and *Cairngorm*. *Aventurine quartz* is spangled through association with glancing flakes of mica or some other platy mineral.

Quartz occurs primarily as a product of crystallisation in igneous masses during cooling, and forms granular interstitial crystals between the other constituents in granite and quartz-diorite, without external crystalline form. It is able to develop well-bounded crystals in highly siliceous lavas, where it separates out before the crystallisation of the ground; but here it is liable to resorption by the still fluid ground as the molten mass nears the surface. Tongues of the glassy ground are then seen to penetrate the crystals, which become reduced to mere round grains. Liquid-inclusions are abundant in the quartz of deep-seated rocks, such as granite, and are probably of secondary origin, indicating an attack upon the mineral. Otherwise quartz remains beautifully transparent and undecomposed, in contrast with the dull appearance of felspars and other minerals round about it. Quartz also forms veins in all manner of rocks, the silica having been brought up in solution. These veins are often milky white, but are easily distinguished from those of calcite by the hardness and the absence of cleavage-surfaces. Sandstones are formed almost entirely of quartz-grains, since quartz remains in river-beds and on shores after other detrital materials have become dissolved or decomposed into fine particles and washed away. Where quartz cements a sandstone, forming a quartzite rock, it is deposited as enlargements of the sand-grains. The fresh quartz is added to the grain in perfect crystalline continuity, so that in thin slices cement and grain show the same optical orientation and interference-colours between crossed nicols. The material thus added to adjacent grains meets along irregular boundaries, and the final effect is that of an interlocked mosaic. Quartzite is thus the hardest rock known.

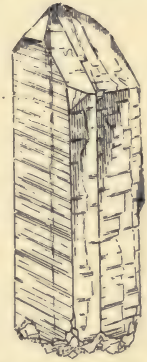


FIG. 87. — Smoky quartz, St. Gotthard.

The ordinary quartz of the mineralogist is the trigonal-trapezohedral form above described, known, as a result of Mügge's researches in 1907, as α-quartz.[1] On heating to 575°, it passes into β-quartz, which appears to be hexagonal-trapezohedral (hexagonal V). This type reverts to α-quartz as it cools, but shows a shattering and cracking, due to the difference of the coefficients of expansion in the two forms. Iddings refers the crystals with good hexagonal outlines seen in quartz-porphyries and rhyolitic lavas to β-quartz.

Considerable discussion has taken place as to the temperature of fusion of quartz, and hence as to the heat required to maintain a granite magma molten in the earth. The separation of minerals from the mixed solutions known as igneous rocks depends, however, on much more than their mere fusion-points. Quartz is stable up to 850°, and remains as such up to 1600° if heated quickly, when it melts. In small fragments, however, when slowly heated in presence of a catalyser, such as sodium tungstate, it turns gradually into tridymite at about 870°, and at 1470° into cristobalite. The melting-point of this final product is about 1600°.

Fenner concludes that quartz must have been formed at temperatures below 870°, and that the silica was probably at one stage in igneous rocks in one of the two "higher forms."[2]

Tests.—Insoluble, except in hydrofluoric acid. Infusible before the mouth-blowpipe. Fuses in borax, but not in microcosmic salt. Even the coloured varieties are colourless in thin sections. No dusky products of decomposition. Crystal-outlines rarely seen in rock-slices.

Opt.—Refractive indices, $\omega = 1{\cdot}5442$, $\epsilon = 1{\cdot}5533$. Hence weak birefringence, giving grey and white tints between crossed nicols in thin slices and clear bright colours in thicker ones. Basal sections isotropic; thick sections, however, show rotatory polarisation. Hence in convergent light thick basal sections show a circular coloured area at the centre, the rays of the black cross starting from its margin.

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[1] See especially F. E. Wright, *Amer. Journ. Sci.*, **28** (1909), 322, and **27** (1909), 423.

[2] A. L. Day and E. S. Shepherd, *Amer. Journ. Sci.*, **22** (1906), 275; and Shepherd, Rankin, and Wright, "Binary Systems of Alumina with Silica, etc.," *ibid.*, **28** (1909), 323; J. P. Iddings, "Rock Minerals" (1911), 539; and C. N. Fenner, "The Various Forms of Silica," *Journ. Washington Acad. Sci.*, **2** (1912), 472.

Chalcedony. SiO_2.—Bluish-grey or variously stained; translucent; vitreous lustre. Fibrous or granular, lining cavities in igneous rocks or occurring as concretions, which are often pseudomorphs of limestone. It appears that, when more complete crystallisation takes place, quartz is produced.[1] H. = 7. G. = about 2·6.

Chalcedony often forms mammillated masses (Fig. 88), and layers of it play a large part in the building up of *agate.* Its coloured forms have received various names, and were well known to the ancients as ornamental stones and gems. Opaque chalcedony, red or brown or green, is called *Jasper.* The bright red varieties of jasper are common as pebbles on seashores *Carnelian* or *Sard* is a more translucent red form. *Prase* and *Chrysoprase* are translucent green. *Heliotrope* or *Bloodstone* is prase spotted with red jasper. Chalcedonies of various kinds were always prized for the cutting of seals. Chalcedony is sometimes found replacing fossil wood.

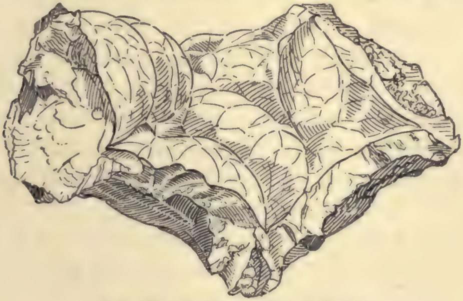

FIG. 88.—Chalcedony, Iceland.

Flint and *Chert,* materials that cannot well be discriminated, are common types of chalcedony. In thin section, they usually show traces of organisms, such as siliceous sponges or radiolaria, which abstracted their silica from the water in which the surrounding rock was laid down. But additional silica, perhaps derived also from organic skeletons, has concreted about these remains, since flint shows all the structure of the limestone in which it occurs, the silica replacing the shells of foraminifera or oolitic grains, and sometimes wrapping round the tests of echinoids or the shells of molluscs, which remain in a calcareous state. The fine mud, originally calcareous, in the interior of such fossils may be replaced by the infiltered silica, and internal casts of organic remains in flint are common, and become washed out into surface-gravels. Flint may also be deposited in joint-planes of rocks, or as a cement to sand-grains, as in the cherty greensands of southern England. The irregular nodular flints from the Chalk formation, when broken across, appear black, with a fine conchoidal fracture; but they have a white crust, which is due to the removal of some of their silica, leaving a porous coat. In gravels, these flints often turn brown, through oxidation of iron associated with them. The chert or flint of the British and Irish Carboniferous Limestone forms more clearly stratified masses, but is also a pseudomorph of the limestone along layers rich in the remains of tetractinellid sponges. Dull black flint is still used as a "touchstone" to receive the streak of gold, when the value of an article is being estimated.

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[1] C. N. Fenner adduces new reasons for regarding chalcedony as a distinct species. *Journ. Wash. Acad. Sci.*, **2** (1912), 476.

Opt.—The fibres of chalcedony have a refractive index slightly lower than that of ω in quartz. Their direction of elongation is that of the fastest ray; hence, if they are quartz, they must be elongated parallel to the basal plane. A group of radial fibres of chalcedony shows, as all such aggregates must, a black cross between crossed nicols without the converging lens, since there are always four fibres lying along two lines perpendicular to one another in a position of extinction. Flint usually shows between crossed nicols merely a minutely granular effect.

TRIDYMITE. SiO_2.—Colourless and transparent. Rhombic at ordinary temperatures (α-tridymite); hexagonal at about 130° (β-tridymite). Occurs as fragile six-sided plates, often in triplets, whence its name, the individuals radiating from a common line. H. = 7. G. = 2·3. The small plates may be seen in cavities of highly siliceous lavas, as in rhyolite in the Cerro San Cristobal, Mexico, and in Co. Antrim, and in trachyte in the Siebengebirge near Bonn. Tridymite thus arises as a final product during the consolidation of the rock, and probably at a temperature above 870° (see under Quartz). *Asmanite*, a form of silica found by Story Maskelyne in a meteorite of Breitenbach, is probably tridymite.

Tests.—Note the low specific gravity.

Opt.—Colourless. Average refractive index = 1·47, and is thus well below that of Canada balsam. Very weak birefringence.

CRISTOBALITE. SiO_2.—White bipyramids like octahedra, and is of interest as giving a third and approximately cubic type of crystallised silica. H = 7. G = 2·3, like that of tridymite. Found with tridymite in the lava of Cerro San Cristobal, Mexico.

As already stated, powdered quartz when slowly heated passes into tridymite in presence of a catalyser at 870°, and this passes into cristobalite (which was formerly in such experiments regarded as tridymite) at 1470°. The reverse process from tridymite to quartz takes place with extreme slowness, and also requires a catalyser to render it apparent.[1]

Opt.—Refractive index = 1·49, slightly higher than in tridymite. May show weak birefringence (α-cristobalite), but becomes truly isotropic (β-cristobalite) at 175°. The octahedral habit implies that the crystals were formed above this temperature.[2]

Opal. SiO_2, with some H_2O, usually under 10 %.—The non-crystalline form of silica. Colourless to bluish or variously stained. The milky blue types appear brown by transmitted light, a phenomenon described in this and other bodies as "opalescence." H = 5·5 — 6·5. G = 2·2. Opal lines cavities in rocks in clear, colourless, mammillated forms (*Hyalite*); it furnishes opalescent layers in most agates; and examples which show a play of iridescent colours, owing to the association of layers of different refractive indices, are known as *Precious opal*, and are in much demand as gems. Precious opals are found as infillings of cavities in highly siliceous lavas, such as the rhyolites of Hungary and Mexico; and in Queensland as strings and veins in a highly ferruginous brown sandstone. An inferior milky type is sometimes styled *Semiopal*, though mineralogically it is good opal. Red translucent forms are known as *Fire-opal.*

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[1] Day and Shepherd, "The Lime-Silica series of Minerals," *Amer. Journ. Sci.*, **22** (1906), 275; Shepherd, Rankin, and Wright, *ibid.*, **28** (1909), 323; C. N. Fenner, *Journ. Wash. Acad. Sci.*, **2** (1912), 472.

[2] Gaubert, *Bull. Soc. Min.*, **27** (1904), 244, and F. E. Wright, *Amer. Journ. Sci.*, **28** (1909), 323.

The *Siliceous sinter* deposited by geysers as white crusts, and ultimately forming coherent masses, is primarily opal, though passing into chalcedony and even quartz. Opal is, in fact, unstable, and any opaline deposits of early geological date have long since become represented by crystalline forms of silica.

Wood-opal is wood the tissues of which are replaced by opal; but much of the material so called is really chalcedonic. Diatoms, the majority of radiolaria, and the siliceous sponges make their hard skeletons of opaline silica, which dissolves in part in existing seas on the death of the organism, and which becomes lost in geological time unless chalcedonic change has taken place. The silica so removed in solution no doubt plays a large part in the formation of flint.

AGATE results from the deposition of successive layers of opal, chalcedony, and quartz, according to the conditions prevalent from time to time, within cavities of rocks. Agates thus most commonly arise in the hollows left by the escape of gases from viscid lavas. A residual space often remains at the centre of the agate, and the slow deposition of the last contents of the cavity has usually allowed quartz crystals to separate out. When the rock decays, the agates fall out like pebbles, large and small, and their insoluble character leads to their accumulation in certain beaches. Not content with their natural colours, such as the black and white alternating layers in *Onyx*, or the frequent jaspery red examples, the dealers in cut stones often introduce artificial stains, which are absorbed by the opaline layers.

Titanium.

The best general test for titanium in minerals is that in HCl, after fusion with sodium carbonate, as described under Ilmenite in the iron series. The borax bead in O.F. is colourless, in R.F. yellow to brown; microcosmic salt gives O.F. colourless, R.F. violet (or O.F. flesh-red and R.F. dark red-brown when iron is present).

Rutile. $TiTiO_4$ ($= TiO_2$); isomorphous with zircon, $ZrSiO_4$, and thorite, $ThSiO_4$.[1]—Deep red-brown or crimson-red, with almost metallic lustre. Rarely translucent, except in microscopic crystals. Tetragonal I; prisms of both orders capped by pyramids. $a : c = 1 : 0{\cdot}644$. Often twinned on a face of the second-order pyramid $\{101\}$, so as to produce knee-shaped twins, which are sometimes heart-shaped in small crystals. By repeated twinning, a rosette of prismatic crystals results. H. = 6—6·5. G. = 4·2.

While delicate and glancing capillary rods of rutile occur, enclosed in some rock-crystals, and handsome stout forms are found in cavities of rocks, the geological interest of the mineral lies in its very wide distribution as microscopic crystals. It occurs as minute brown rods in granites and other igneous rocks, and its exceptional specific gravity allows it to be concentrated in the sands derived from such masses. In clays and their altered representatives, slates and schists, small translucent yellow crystals, recognisable by their twinning, abound to an extraordinary extent, and probably represent titanium that was once locked up in ilmenite or still more often in titaniferous mica. This is almost certainly their origin in chlorite-schist. Rutile also occurs as translucent purple-brown or brown inclusions in some micas.[2]

Tests.—Insoluble in HCl. Infusible. Gives good titanium reactions in blowpipe-work.

Opt.—Refractive index, $\omega = 2{\cdot}616$, $\epsilon = 2{\cdot}903$; positive.

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[1] W. T. Schaller, following Brögger and Prior, regards rutile as a titanate, $TiO . TiO_3$, *U.S. Geol. Surv., Bull.* 509 (1912), 12.

[2] W. O. Snelling reviews the occurrence and uses of rutile and other titanium ores in *U.S. Geol. Survey*, "Mineral Resources," 1901.

Birefringence very strong (0·287). Hence shows dark outlines against other minerals in rock-slices. Pleochroic in yellow-brown tints.

ANATASE. TiO_2.—Yellowish when translucent; but the high refractive index and the inclination of the crystal-planes render it practically opaque.[1] The surface appears blue-black, with a brilliant and almost metallic lustre. Tetragonal I, like rutile, but $a : c = 1 : 1{\cdot}777$. Common form small steep bipyramids. H. = 6. G. = 3·9.

Tests.—Like rutile.

Opt.—Refr. index nearly as high as that of rutile, but birefringence only 0·061. Negative.

BROOKITE.—A rhombic form of TiO_2, in brown, translucent, and sometimes platy crystals. H. = 6. G. = 4.

G. T. Prior (*Min. Mag.*, **13**, 1903, 220) proposes formulæ for anatase and brookite on the basis of assumed molecular volumes. The "molecular volume" of a substance equals its molecular weight multiplied by the volume in c.c. of 1 gramme of the substance. This latter, the "specific volume," is obviously the reciprocal of the specific gravity, and much depends, in the case of a mineral, on the selection of the specific gravity. Anatase has a close crystallographic resemblance to calomel, Hg_2Cl_2, and to matlockite, Pb_2Cl_2O. Its molecular volume becomes similar if we assign to it the formula Ti_4O_8. Brookite, compared with tantalite and hübnerite, should on the same grounds be Ti_6O_{12}.

Zirconium.

Zircon. $ZrSiO_4$.—An orthosilicate, but retained here as the representative of zirconium in rocks, and on account of its isomorphism with the oxides rutile and cassiterite. Colourless in microscopic crystals; in larger examples commonly yellow-brown to red-brown. Adamantine lustre. Tetragonal I. $a : c = 1 : 0{\cdot}640$. Common forms, first and second order prisms and bipyramids, with the ditetragonal bipyramid {311} (Fig. 23). Untwinned in rock-forming examples. H. = 7·5. G. = 4·5; variations on heating were noticed by Damour and

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[1] See J. Joly, *Sci. Proc. R. Dublin Soc.*, **9** (1901), 475.

Church. S. Stevanovic has shown that some zircons have as low a specific gravity as 4·0, and this is unchanged by heating; another group yields 4·7, similarly unchanged; while there is a third group the members of which increase in density from 4·0 towards 4·7 on ignition in a Bunsen burner.[1]

Zircon is common in minute forms in crystalline igneous rocks, developing at an early stage, and becoming, like rutile, embedded in other minerals. When enclosed in mica, amphibole, chlorite, or cordierite, it causes a dark colouration of the mineral round about it. This effect is not, moreover, confined to zircon, similar "halos" occurring about rutile, orthite, etc. The stained area is pleochroic, but probably only because coloured specimens of the including mineral are pleochroic. J. Joly, in 1907, suggested that the halos were due to the influence of a radioactive substance existing in the included mineral, and pointed out that the diameter of the halo agreed with the distance to which a particular emanation could transmit its energy. From the occurrence at times of a darker halo within a lighter one, Joly was able to indicate the effects of two kinds of radiation, and he recognised rays both from radium and from thorium.[2]

The larger zircons, occurring often in nepheline-syenites, resemble yellow topaz, but exhibit short square prisms. Red-brown examples are the jewellers' *Hyacinth*, and colourless or smoky varieties from Ceylon are called *Jargon*, whence the name of the mineral and of the element zirconium.

Like rutile, zircon becomes concentrated as minute crystals in sands, as in the Bagshot Sand of Hampstead Heath. It was the source of the oxide first used for incandescent gas-mantles.

Tests.—Insoluble in HCl. Infusible. Glows strongly in the flame. H. and G. characteristic.

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[1] See discussion by L. J. Spencer, "On Zircon from Ceylon," *Min. Mag.*, **14** (1904), 47.

[2] "Pleochroic halos," *Phil. Mag.*, Mar. 1907, 381; Feb. 1910, 327; and J. Joly and A. Fletcher, *ibid.*, Apr. 1910, 630. O. Mügge has artificially stained some of the including minerals by the action of radium bromide; *Centralbl. für Min.* (1907), 397, and (1909), 65.

Opt.—Refr. index about 1·95. Birefringence about 0·05, and hence unusually strong.

Tin.[1]

STANNINE. $SnCu_2FeS_4$. Sn 25%.—Steel-grey to black, but often yellowish by admixture with copper pyrites. Metallic lustre. Tetragonal VI., like copper pyrites (L. J. Spencer, *Min. Mag.*, **13**, 1901, 62). H. = 4. G. = 4·5. Called "bell-metal ore" by Cornish miners.

Cassiterite (Tinstone). $SnSnO_4$ (= SnO_2).[2]—Pale, translucent brown to deep brown and black; adamantine lustre. Tetragonal I. Crystals and knee-shaped twins, as in rutile (Fig. 89); the first and second order pyramids occurring together on the end of the square prism often attract attention. $a : c = 1 : 0·672$. A member of the rutile-zircon-thorite series. H. = 6—7. G. = 6·5—7.

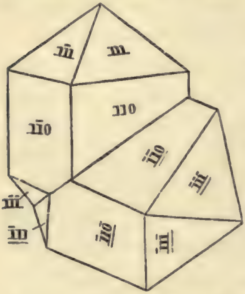

FIG. 89.—Crystal of cassiterite twinned on $(0\bar{1}1)$.

This handsome and heavy mineral is the great source of tin, but is unfortunately of restricted occurrence. It is found in veins throughout decomposed granite and gneiss, and is accompanied by indications of an attack by subterranean gases on the rock. The felspar may be completely kaolinised, or even removed and replaced by quartz and the fluorine-bearing mineral topaz. Fluorspar, another indication of fluorine, may occur, and wolfram and tourmaline are common associates. The decomposed rock-mass suffers readily from denudation, and the high density of the "tinstone" leads to its concentration in river-valleys as *Stream-tin.* Such alluvial deposits spread from the granite areas of the Malay Peninsula across the low ground southward, covering a wide area now broken into islands. *Wood-tin* is a concretionary form, with radial fibres, resembling limonite, but easily distinguished by its weight.

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[1] A useful "Bibliography of the Geology and Mineralogy of Tin," by F. L. Hess and Eva Hess, appears in the *Smithsonian Miscell. Collections*, **58**, No. 2 (1912), occupying 408 pp.

[2] W. T. Schaller prefers to regard cassiterite as a stannyl metastannate $SnO.SnO3$ (*U.S. Geol. Surv., Bull.* 509, (1912), 12).

Tests.—If tinstone is likely to occur in a concentrate gathered from alluvium, place the concentrate in a hollow in a block of zinc, and cover it with equal parts of HCl and water. Wash with water for two or three minutes, when any cassiterite present wlll be found reduced on its surface to shining metallic tin. A zinc pan or spoon may be used, but soon becomes eaten through.[1] The blowpipe-tests are very effective; white oxide forms on charcoal, and turns blue-green after thorough reheating with a drop of cobalt nitrate. If the cassiterite is powdered with one volume of charcoal and two volumes of sodium carbonate, reduction to metallic tin is easily effected on charcoal. The tin bead or beads may be looked for by cutting out the slag and pressing it under water in an agate mortar. The metal may then be tested by treating in O.F. on charcoal. Tin at once forms a sublimate of white oxide along the line of the flame, and the bead soon crumbles down also into oxide; lead, on the other hand, gives an orange sublimate, and the bead is thinly coated with this on cooling; while silver furnishes no sublimate, and remains bright and shining.

Opt.—Is seen sometimes in thin slices of granitoid rocks, and is yellowish, with occasional darker zones. Shows the irregularities of the surface strikingly, the refr. index being about 2. Birefringence 0·099. Pleochroic in yellowish-brown tints.

Cerium.

Ceria has assumed importance as a glowing oxide for incandescent gas-mantles, 1 % of ceria (CeO_2) and 99 % of thoria (ThO_2) proving a satisfactory mixture. Thoria is less luminous if used alone.

CERITE. $H_6Ce_4Si_3O_{15}$.—Though a silicate, cerite may be treated here Reddish-brown. Rhombic. H. = 5·5. G. = 4·9.

MONAZITE. (Ce,La,Di)PO_4, with some $ThSiO_4$.—Usually pink-brown or yellow-brown. Vitreous to resinous lustre Monoclinic. H. = 5·5. G. = 5. Becomes washed from granitoid rocks into sands, where it is concentrated on account of its specific gravity. Is a considerable source of thoria as well as ceria.[1]

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[1] See *Geol. Surv. W. Australia, Bull.* **32** (1908), 12.

Lead.

The yellow encrustation of lead oxide on charcoal may be distinguished from that of bismuth when sulphur and potassium iodide are added to the mineral under examination. The sublimate is then orange-yellow, not red. The metallic bead of lead is malleable and marks paper. See tests for cassiterite.

Galena. PbS. Pb 86 %.—Lead-grey; bright metallic lustre on fracture. Cubic I; combinations of cube and octahedron common (Fig. 90). Cleavage cubic. H. = 2·6. G. = 7·5.

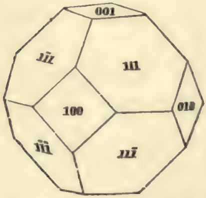

FIG. 90.—Crystal of galena.

The common ore of lead, often massive, but even then showing glancing cleavage-surfaces. Silver is almost always present, and is now more important than the lead from the point of view of the prospector. In Leadville, Colorado, the argentiferous galena also contains gold.

Tests.—The silver may be obtained by cupellation. The metallic bead produced by reduction is treated in O.F. on a cupel, or basin-like surface of bone-ash. The bead becomes covered with an iridescent fluctuating film of oxide, and the lead is gradually oxidised away. Any bead remaining after the play of colours has ceased consists of the silver, and of the gold if this is present. On dissolving this bead in nitric acid, gold may remain in a powdery form, and can be melted up into a button.

JAMESONITE (PLUMOSITE), $Pb_2Sb_2S_5$ (= $2PbS.Sb_2S_3$), and BOULANGERITE, $Pb_5Sb_4S_{11}$ (= $5PbS.2Sb_2S_3$), may be mentioned as types of grey sulphantimonites of lead. Both are rhombic.

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[1] On the separation of thoria from ceria in monazite, see J. Mingaye, *Rec. Geol. Surv. N.S. Wales*, **8** (1909), 276.

Bournonite, $CuPbSbS_3$, with Pb 42·38%, is another dark grey rhombic ore.

Clausthalite is interesting as a selenide, PbSe, and is another lead-grey ore, named from Claustal in the Harz Mountains.

Minium, Pb_3O_4, is a red oxide found as crusts upon galena.

Cerussite. $PbCO_3$.—Colourless or dull white; often translucent. Somewhat resinous lustre on fracture. Very brittle. Rhombic I. $a:b:c = 0·610:1:0·723$. Crystals often elongated along the c-axis and striated. H. = 3—3·5. G. = 6·5. Common in all lead-mines.

Tests.—Effervesces when heated in HCl. Easily reduced to lead on charcoal. The specific gravity calls attention to it, and the absence of sulphur distinguishes it from anglesite.

Phosgenite, $PbCO_3.PbCl_2$, is also a translucent, colourless, white or yellowish ore, with G. = 6. It is, however, rare.

Tests.—The chlorine may be found by the flame-reaction in a microcosmic salt bead saturated with copper. The operation should be performed on charcoal, not on a platinum wire.

Pyromorphite. $(PbCl)Pb_4(PO_4)_3 = 3Pb_3(PO_4)_2 . PbCl_2$.—Some Ca replaces Pb and some As replaces P. Isomorphous with mimetite, vanadinite, and apatite. Commonly yellow-green, but sometimes orange or even purple. Hexagonal III, with stout short prisms and basal planes predominant, $a:c = 1:0·7362$. Prism-faces sometimes curved, so that the crystal is barrel-shaped. Sometimes elongated and fibrous. H. = 3·5—4. G. = 7.

Tests.—When fused before the blowpipe, but just short of reduction, cools as a somewhat globular mass with crystalline facets, whence the name ("taking a form under fire" or "fire-form"). Gives, when moistened with H_2SO_4, a good double flame, the blue of lead within and the green due to phosphorus without. Easily reduced to metallic lead.

Mimetite, $(PbCl)Pb_4(AsO_4)_3$, is the corresponding arsenate, graduating into pyromorphite and closely similar. Colour will not distinguish them, but blowpipe-tests are easy.

Mimetite is much the rarer of the two species, and is named from its imitation of pyromorphite.

Vanadinite, $(PbCl)Pb_4(VO_4)_3$, is the corresponding vanadate. Orange to red-brown.

The presence of chlorine in these three ores must not be overlooked. In apatite, however, fluorine is more common than chlorine. The isomorphous relations of the series are well stated in Miers, "Mineralogy" (1902), 513.

Anglesite. $PbSO_4$.—Colourless and transparent or white and opaque. Much like cerussite, but rarer. Rhombic. H. = nearly 3. G. = 6·3. Often found in cavities of galena, as at Monte Poni in Sardinia, arising as an alteration-product. Named from Anglesey, where it was found in the Parys Mine.

Tests.—The sulphur is detected after fusion with sodium carbonate and placing on a moistened silver coin.

Crocoise (Beudant, 1832), (Crocoisite of von Kobell, 1838, and Crocoite of Breithaupt, 1841). $PbCrO_4$.—Bright red; streak orange. Lustre nearly adamantine. Translucent. Monoclinic; elongated prisms. H. = 2·5—3. G. = 6. A somewhat rare ore of brilliant colouring; darkens on exposure to light.

Tests.—The chromium appears in the beads of borax and microcosmic salt, which must be prepared on charcoal.

Wulfenite. $PbMoO_4$.—Yellow to orange-red. Tetragonal IV; crystals commonly square and tabular, with development of third order prisms. Wulfenite is thus much like the tungstate scheelite, but is now known to be hemimorphic on the *c*-axis. H. = 3. G. = 6—7. Not common, but forms an ore of molybdenum at Bleiberg in Karinthia.

Stolzite interestingly completes the lead series, being a tungstate, $PbWO_4$. Greenish or yellow. Tetragonal and isomorphous with scheelite.

Thorium.

As already remarked, thoria is extracted from monazite for the incandescent mantle trade.

Thorianite. $(Th,U)O_2$.—Black, sub-metallic. Cubic;

found as small cubes, mostly in alluvium, in Ceylon in 1902. Exceptionally rich in helium, which is probably derived from included radium.[1]

THORITE. $ThSiO_4$.—An orthosilicate, but retained here as a member of the rutile-cassiterite-zircon series, with which it is isomorphous. Yellow to black. Tetragonal I, $a:c = 1:0·640$. H. = 5. G. = 5. The yellow variety has been called *Orangite*.

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[1] Strutt, *Nature*, **79** (1908), 207.

CHAPTER XIII

GROUPS III AND II, INCLUDING ALUMINIUM, MAGNESIUM, CALCIUM, AND ZINC

GROUP III.

Aluminium.

ALUMINIUM most frequently occurs in the form of silicates, and its simple hydrous silicate, kaolin, is the basis of common clays. In any minerals that fuse before the blowpipe-flame, the presence of alumina must be determined by precipitation in the ordinary way; but, in the case of kaolin, colourless corundum, topaz, and other infusible minerals, a powder or splinter of the mineral may be moistened with cobalt nitrate, and strongly heated in O.F. On cooling, a pale blue colour indicates alumina. The blue due to silica in fused silicates is much deeper.

CRYOLITE. $AlNa_3F_6$ (= $AlF_3.3NaF$). F 54·4%.—Colourless and transparent to white. Monoclinic, but with prism-angle 88°, and suggesting, with the perfect basal cleavage, cubic forms. H. = 2·5. G. = 3. Cryolite occurs as a massive vein near Arksut in West Greenland. It has been fully investigated, with its associates, by O. Böggild, of Copenhagen.[1] It is important in the aluminium industry as providing a bath, when molten in the electric furnace, in which metallic aluminium will separate out from bauxite.

Tests.—Fusible in splinters in a candle-flame. In open tube, gives off hydrofluoric acid, which etches a glass slip held over the upper opening. With cobalt nitrate gives the blue colour due to alumina. The absence of silica can be shown by the complete solution of the mineral in microcosmic salt.

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[1] *Zeitschr. für Kryst.*, **50**, 349, and **51** (1913), 591.

Corundum. Al_2O_3.—Grey, blue-grey, or brown-red. Rarely colourless. Transparent coloured varieties are much valued as gems. Usually opaque. Lustre vitreous to adamantine. Trigonal IV; but the common forms are tall hexagonal bipyramids. Twinned repeatedly on rhombohedron-planes, the surfaces of the lamellæ forming fracture-planes that supplement the basal cleavage. H. = 9. G. = 4.

Occurs in granites and other crystalline igneous rocks, in crystals proportioned to the general coarseness of the rock. Also in some altered masses, as in crystalline limestone in Burma. The clear blue variety is *Sapphire*, and the clear pink-red variety is the true *Ruby*. A small granular type, mostly minute sapphire, and often mixed with magnetite, is known as *Emery*. Emery[1] occurs in the marble members of a gneissic series of rocks, and as great boulders, in Naxos and Samos in the Greek archipelago, and is a cheap abrading agent. The artificial crystalline silicon carbide, "carborundum," produced in the electric furnace, is still harder, and has taken its place for many purposes.

The gems (artificial corundum) manufactured by the fusion of alumina have been coloured to resemble the natural ruby. They grow in the oxyhydrogen flame in irregular forms, like candle-grease; but the mass made at any one time consists of one crystal, structurally continuous throughout.[2] The cause of the colour of the natural gems is unknown. Bordas[3] produced various tints in natural corundum, red, blue, green, yellow, etc., by the emanations from radium bromide, according to the distance and intensity of the exciting cause; and these observations led to Mügge's work on the coloured halos surrounding zircon included in cordierite (see Zircon).

Tests.—The hardness and specific gravity should be specially noted. Infusible before the blowpipe. Blue reaction with cobalt nitrate.

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[1] A. Philippson, "Beiträge zur Kentniss der griechischen Inselwelt," *Petermanns Mittheil.*, Ergänzungsheft **134** (1901).

[2] See W. McLintock, "Guide to the Collection of Gemstones in the Museum of Practical Geology" (London, 1912), 31.

[3] *Comptes Rendus*, 28 Oct. 1907.

Opt.—Negative. Refr. index of both rays fairly high, near 1·76, and birefringence weak (0·009). In its strong relief and low interference-colours, corundum thus resembles zoisite in rock-slices.

Coloured translucent crystals show distinct pleochroism, the axis-colours being darkest for the ordinary rays, that is, for vibrations perpendicular to the optic axis. In common corundum in rock-slices, the colour is blue for this direction and fades into colourless for vibrations parallel to the optic axis (a-axis). The reddish and yellowish axis-colours distinguish ruby from spinel.

DIASPORE, $AlO(OH)$ ($=Al_2O_3.H_2O$), is a colourless or palely tinted rhombic mineral, in elongated prismatic crystals, which is found with corundum in many localities. GIBBSITE (HYDRARGILLITE), $Al(OH)_3$ ($=Al_2O_3.3H_2O$), is similarly white or palely coloured. Occurs as monoclinic six-sided platy crystals, also associated with corundum. The geological interest of these minerals lies in the probability that as a mixture they form the rock known as **Bauxite**, to which a composition of $(Al,Fe)_2O_3.2H_2O$ has sometimes been assigned, on the supposition that it was a distinct mineral species. Bauxite may be pale blue or grey, or strongly coloured by hæmatite or limonite. The ferruginous varieties are known as "laterite," and occur as products of decomposition, under tropical conditions of weathering, of all manner of rocks containing aluminium silicates, such as granites, basalts, shales, etc. Moisture as well as heat seems required for the formation of laterite and bauxite; the process involves the almost complete removal of the silica from the original silicates, but the retention of the alumina as a hydrate. Kaolinisation and laterisation thus present themselves as opposed processes.

T. H. Holland[1] points out, from his wide experience in

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[1] "On the Constitution, Origin, and Dehydration of Laterite," *Geol. Mag.* (1903), 59. See also discussion and references in Clarke, "Data of Geochemistry," *U.S. Geol. Surv., Bull.* 491 (1911), 469, and in "The Interbasaltic Rocks of N.E. Ireland," *Geol. Surv. Ireland* (1912), 6.

India, that dehydration proceeds in the lateritic mass. Gibbsite thus passes into diaspore, while göthite and even hæmatite develop.

Bauxite is used for the production of alum; but the varieties with very small amounts of residual silica, like those from the original locality, Les Baux in Vaucluse, have now become very valuable as ores of aluminium. Pure alumina is extracted from them, and is reduced to the metal in the electric furnace.

SPINEL.—The spinellids (p. 176) rich in aluminium may be mentioned here, since they differ so markedly in their more obvious characters from those that we have included in the iron series of minerals. The typical spinel or *Spinel-ruby* has the composition $MgAl_2O_4$. Colour pink-red, much like ruby; transparent. Cubic I; octahedra. H. = 8. G. = 3·5. *Opt.*—Isotropic. Refr. index 1·715.

Pleonaste, $(Mg,Fe'')(Al,Fe''')_2O_4$, is dark green to black. *Picotite* is a chromium-spinel, with iron, linking pleonaste and chromite. It occurs in some ultrabasic igneous rocks, and is brown-green or brown in thin sections. *Gahnite* is of interest as a zinc-spinel, $ZnAl_2O_4$, connecting the spinels obviously with franklinite, with which it occurs in New Jersey.

The silicates **Andalusite**, SILLIMANITE, KYANITE, TOPAZ, and **Kaolin** are reserved for the separate Silicate group.

WAVELLITE. $2Al_3(OH)_3(PO_4)_2.9H_2O$.—The water present is very variously stated. Colourless to greenish; vitreous lustre. Rhombic I, but usually in radial groups, forming globular concretions, or discoidal forms on joint-planes of slaty rocks. H. = 3·5. G. = 2·3. Is of geological interest from the occurrence of aluminium phosphate in soils; this may be broken up by liming, with the production of aluminium hydrate and calcium phosphate, the phosphorus becoming thus available for plants.

TURQUOISE. $Al_2(OH)_3PO_4.H_2O$ (Miers); $CuOH.6[Al(OH)_2]H_5(PO_4)_4$ (Schaller).[1]—Pale sky-blue. Triclinic. H. = 6. G. = 2·7. Found as an infilling of cavities in lava in Persia, and cut in hemispherical forms as an ornamental stone. The colour is believed to be due to copper; the Virginian specimens contain nearly 8 per cent. of CuO.

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[1] On crystallised turquoise from Campbell County, Virginia, see W. T. Schaller, *U.S. Geol. Survey, Bull.* 509 (1912), 42.

ALUMS.—General formula $R'Al(SO_4)_2.12H_2O$. Cubic. Soluble in water, and therefore rare in nature. They sometimes appear in shaly rocks where iron pyrites oxidises and the aluminous minerals are attacked.

ALUNITE. $K(AlO)_3(SO_4)_2.3H_2O$.—Colourless to white. Transparent or translucent. Trigonal IV. H. = 3·5—4. G. = 2—6. Soluble in H_2SO4. Is used in alum-manufacture, and is regarded as a possible source of potassium and hence as a fertiliser for soils. B. S. Butler and H. S. Gale,[1] in the case of a vein in Utah, urge that ascending solutions extracted the aluminium and potassium from granitoid rocks at a greater depth.

WEBSTERITE (ALUMINITE). $(AlO)_2SO_4.9H_2O$.—White earthy masses in clay. H. = 1·5. G. = 1·66. Soluble in acids.

GROUP II.

Glucinum (*Beryllium*).

It appears that the name glucĭnum for the element has priority, but that the symbol Be has become too well established to be changed.

CHRYSOBERYL. $BeAl_2O_4$.—A yellow to greenish transparent gemstone.[2] Rhombic. H. = 8·5. G. 3·7. Refr. index about 1·75.

Two silicates are most conveniently considered under this head:—

PHENACITE. Be_2SiO_4.—A colourless transparent gemstone. Trigonal V, with second and third order rhombohedra. H. = 7·5—8. G. = 3.

Opt.—Refr. index, $\omega = 1·6540$, $\epsilon = 1·6697$.

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[1] "Alunite," *U.S. Geol. Survey, Bull.* 511 (1912). Contains a notice of occurrences and use in Italy and elsewhere.

[2] On the interesting darkly coloured variety *Alexandrite* see McLintock, "Guide to the Collection of Gemstones in the Museum of Pract. Geology" (1912), 60.

BERYL. $Be_3Al_2Si_6O_{18}$.—Bluish to emerald-green. Sometimes, as a rock-constituent, opaque and blue-green or yellowish. Vitreous lustre. Hexagonal; prism terminated by small low prism-planes and basal planes. Often striated and almost cylindrical. H. = 7·5—8. G. = 2·7. Large crystals occur in veins, with quartz, tourmaline, etc., in some granites. The gemstone types are the delicate bluish prisms styled *Aquamarine* and the brilliant green *Emerald*. Strutt notes that beryl is anomalous in being rich in helium though poor in radium.[1]

Tests.—Insoluble in acids. The specific gravity, which is low for a gemstone, is useful.

Opt.—Negative. Refr. index about 1·587; consequently no very strong relief. Birefringence low (about 0·007, between quartz and orthoclase). Only feebly pleochroic.

Magnesium.

Magnesia gives a pale pink reaction after moistening with cobalt nitrate and heating strongly in O.F.; but this is seldom traceable in mineral compounds, especially where iron is also present. Precipitation with hydrogen sodium phosphate is necessary in most cases.

BRUCITE. $Mg(OH)_2$.—Colourless, transparent. Trigonal IV; tabular crystals with good basal cleavage. Plates flexible, resembling gypsum. H. = 2·5. G. = 2·4. Occurs in clayey rocks and as a product from magnesium silicates in serpentine.

Tests.—Infusible. Gives magnesium reaction with cobalt nitrate. No sulphur (distinguished thus from gypsum).

MAGNESITE. $MgCO_3$.—Opaque white, dull. Trigonal IV, but crystals rare. Angle over polar edges of rhombohedron 107° 24′. H. = 4. G. = 3. Occurs as a product of alteration of rocks rich in magnesium silicates, and is sought after as an infusible brick-making material for furnaces. It is sometimes calcined to MgO, when, however, it takes up a little CO_2 from the air. $MgCl_2$ is then added and the mixture makes a cement.

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[1] *Nature*, **79** (1908), 207.

Tests.—Dissolves with effervescence in hot HCl. Gives magnesium reaction with cobalt nitrate.

Dolomite. $MgCa(CO_3)_2$. $CaCO_3$ 54·35, $MgCO_3$ 45·65%, or CO_2 47·8, CaO 30·4, MgO 21·8%.—Usually some Fe, giving a brownish tint to exposed examples. Colourless, white ("pearlspar" type), or greyish; often brown. Trigonal V, the low symmetry being shown by corrosion-figures. $a : c = 1 : 0·8322$. Otherwise resembles calcite, but, in place of prismatic and scalenohedral forms, simple rhombohedra are far more common than in calcite. Angle over polar edges of rhombohedron 106° 15′. The faces are often warped and curved, and quaint saddle-shaped crystals sometimes result. Perfect rhombohedral cleavage. H. = nearly 4. G. = 2·85.

Dolomite forms considerable masses of rock, but is usually a modification of limestone, magnesium having become substituted for calcium. Along cracks in the blue-grey Carboniferous Limestone of the British Isles, brown bands of dolomite may be seen, resembling intrusive dykes. Coarse crystallisation may have taken place, and the original structure of the limestone is usually lost; but the dolomite is clearly a replacement of the limestone and not merely the infilling of joints. Thick beds of limestone may thus become dolomitised, their structures and fossils becoming obliterated. Modern coral-reefs undergo this process, and it has been suggested that calcium carbonate is dissolved out of them into the sea-water, until the magnesium carbonate that exists in many coral skeletons is brought up to molecular equality with the remaining calcium. It may be regarded, however, as certain that the magnesium is introduced from the magnesium sulphate and chloride in the sea; aragonite, which is the form of calcium carbonate in most reefs, is more susceptible than calcite to the change. E. W. Skeats[1] shows that in recent reefs some excess of $CaCO_3$ tends to remain, 40% of $MgCO_3$ being a common figure in the dolomitised portions. The most striking instances of the conversion of calcium carbonate rock into dolomite rock are the great masses that form the pinnacled Dolomite Alps of Tyrol.

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[1] "Limestones from upraised Coral Islands," *Bull. Mus. Comp. Zool., Harvard*, **42** (1903), No. **2**; and "Origin of the Dolomites of Southern Tyrol," *Quart. Journ. Geol. Soc. London*, **61** (1905), 97.

A shrinkage of 4·56 % takes place when calcite is replaced by dolomite, and hollows are often seen in the resulting mass, in which calcite sometimes crystallises, having been introduced by later infiltration. Where aragonite, on the other hand, is thus replaced, an expansion must occur, unless some of the calcium carbonate is simultaneously removed.

Some dolomite rocks appear to have been deposited chemically, with rock-salt, in the evaporation of old lagoons. The crystalline concretions in the dolomitic limestone of Sunderland, which often pass as dolomite, consist of calcite.

The dolomitisation of limestone has a commercial aspect, since a comparatively small percentage of magnesium carbonate prevents a limestone from being utilised in cement-manufacture. While dolomite rocks form good building stones for country use, the greater solubility of calcite in the carbonic acid of atmospheric waters causes partially dolomitised limestones to become loose and granular; while in towns, where sulphuric acid is common, magnesium sulphate is formed, which is even more soluble in water than calcium sulphate.[1]

Tests.—The occurrence of rhombohedra, often with curved faces, suggests that the mineral is not calcite. It effervesces briskly only when the hydrochloric acid is heated; this fact, however, may be masked in dolomitic limestones by the presence of calcite. Dolomite scratches calcite and has a higher specific gravity. Lemberg's[2] test is useful where dolomite and calcite or aragonite are associated, and may be applied to thin slices cleaned from balsam. Dissolve 4 parts of aluminium chloride in 60 parts of water, and add 6 parts of dry logwood. Filter the violet solution. Calcite or aragonite treated with it for seven minutes remains violet after washing; dolomite does not show coloration beyond, perhaps, a few blue spots. Calcite and aragonite, in fact, decompose, and aluminium hydrate is thrown down, which absorbs the hæmatoxylin dye.

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[1] J. S. Howe, "Geology of Building Stones" (1910), 353.

[2] *Zeitschr. d. deutsch. geol. Gesell.*, **11** (1888), 357.

Opt.—In thin sections of rocks, crystal-outlines are seen far more frequently with dolomite than with calcite. Twinning is less frequent in dolomite. Negative, like calcite; $\omega = 1{\cdot}70$, $\epsilon = 1{\cdot}51$. Birefringence 0·18, stronger even than in calcite. Interference-colours very high. For a reaction when the polariser alone is used, see under the optical properties of calcite.

ANKERITE, $Ca_2MgFe(CO_3)_4$, with sometimes Mn, is a link in a chain of trigonal minerals between calcite, dolomite and siderite, and has been shown to be the common carbonate in the joint-planes of coal in England, probably arising from downward infiltration.[1]

TALC. $H_2Mg_3(SiO_3)_4$.—See Silicates.

BORACITE. $Mg_7B_{16}Cl_2O_{30}$.—Colourless to white or faintly greenish. Cubic III at 265°, but shows optical and structural anomalies below this temperature.[2] The forms are usually small neatly developed cubes truncated along their edges by the rhombic dodecahedron, the tetrahedral character being apparent by the planes added on the solid angles. The four diagonal axes of the cube are polar electrical axes when the crystal is heated, but cease to be so when 265° are reached. H. = 7. G. = 3. Occurs with gypsum, anhydrite, rock-salt, and other products of the evaporation of lagoons or lakes.

EPSOMITE. $MgSO_4.7H_2O$.—Colourless. Rhombic III, in almost square prisms terminated by the bisphenoid (Fig. 21). Usually botryoidal or encrusting. Soluble in water; taste somewhat bitter.

Common as a fibrous efflorescence in dry mines. Crystals abound in the earth of the floors of the Kentucky caves, which are formed in limestone. Large quantities are being deposited, together with gypsum, in the Gulf of Kara-boghaz in the eastern Caspian, a region of high evaporation.[1] Is well known in solution in mineral springs, being named after the old "spa" of Epsom.

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[1] T. Crook, *Min. Mag.*, **16** (1912), 217.

[2] See description by Miers (after Mallard), "Mineralogy," 389.

KIESERITE, $MgSO_4.H_2O$, is of interest as one of the Stassfurt series of salts (see Carnallite), underlying the carnallite layer in the mines.

Calcium.

FLUORSPAR. CaF_2.—Colourless to purple-black, being very variously stained. Yellow and red varieties occur, but by far the commonest tints are violet and green, the colour being irregularly splashed, as it were, through the crystal, but imparting a fairly uniform effect to the uncut mass. Zoning is common, green zones sometimes succeeding violet ones. Transparent to translucent. Cubic I; common form the cube (Fig. 52). The hexakis-octahedron appears sometimes on the solid angles, two of its planes running along and bevelling obliquely each of the three edges at each of the eight solid angles. "Vicinal" faces, departing little from those of the cube, such as those of a low-pitched four-faced cube, are occasionally noticeable as one turns the crystal in the hand. Cleavage nearly perfect, octahedral, the angles of large cubes often becoming accidentally truncated.

H. = 4. G. = 3·18. Occurs as a secondary product where hydrofluoric vapours have risen in the earth's crust, as in the altered granites that bear cassiterite and topaz; also in limestone areas, as in Derbyshire, where the fine crystals go by the name of "Blue John."

Tests.—Soluble when heated in H_2SO_4, with formation of hydrofluoric acid, which etches a glass slip held over the tube in which the operation is going on. Calcium flame.

Opt.—Isotropic. Refr. index 1·434, and thus shows considerable relief in rock-slices, for the unusual reason that its refr. index is lower than that of the balsam. Usually appears in sections as interstitial patches, without crystal-outlines, and with irregular flecks of pale violet staining. Some examples show a greenish fluorescence on heating, the variety *Chlorophane* being named on account of the exhibition of this feature with especial brilliance.

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[1] *Nature*, **69** (1904), 281.

Calcite (Calcspar; calcareous spar). $CaCO_3$. CaO 56, CO_2 44%.—Colourless and transparent to nearly opaque white. Rarely colour-stained. Trigonal IV; the type of the scalenohedral and rhombohedral class. $a : c = 1 : 0{\cdot}8543$. Crystals usually combinations of the hexagonal prism, the ditrigonal scalenohedron, and a rhombohedron (Figs. 44, 46, and 91). When the rhombohedron predominates, the forms may be acute or distinctly obtuse and flattened. The latter type is known as *nail-head spar*. The elongated scalenohedral type forms the *dog-tooth spar* of miners. The unit rhombohedron $\{10\bar{1}1\}$ has the angle over its polar edges $= 105° 5'$. Cleavage perfect, parallel to the planes of this unit form, so that all types of calcite crystal break up into rhombohedral fragments with angles the same as those of the unit form. The cleavage is often well seen within transparent crystals, and its relation to the external forms present can be recognised (Fig. 92).

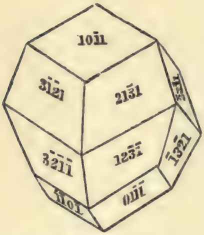

FIG. 91.—Crystal of calcite, with scalenohedron and positive rhombohedron.

Twinning on one or more planes of the negative rhombohedron $\{01\bar{1}2\}$ is common and repeated, that is, on planes that would, if developed, truncate polar edges of the cleavage-rhombohedron. This

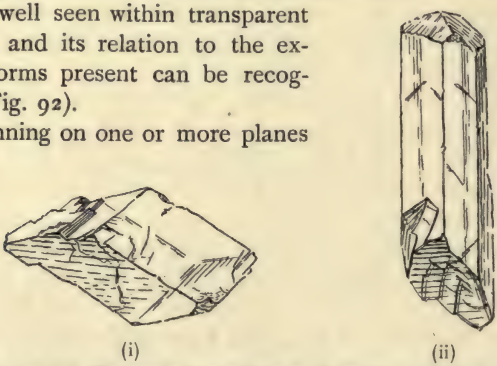
(i) (ii)

FIG. 92.—(i) Cleavage rhombohedron of calcite placed in the same crystallographic position as the crystal (ii), in which cracks due to the cleavage can be seen.

twinning takes place on what are truly "gliding planes," since the molecules on one side or other of such a plane can adopt under pressure the twin-orientation in regard to those on the other side. Baumhauer has shown how this twinning can be artificially produced. Take a cleavage-form and hold it so that it rests on a polar edge; another polar edge will lie horizontally above this, and at one end of the form a plane unites the two edges, the upper edge making an obtuse angle with it (Fig. 93). Press a knife-blade vertically down on this edge, and a gliding plane or planes will develop beneath it. The molecules between the knife-edge and the oblique plane of the cleavage-form alter their positions, and some move outward so as to build up a new face, with a constant re-entrant angle between it and the original face. This is the twin form that commonly occurs in nature, sometimes on a very large scale.

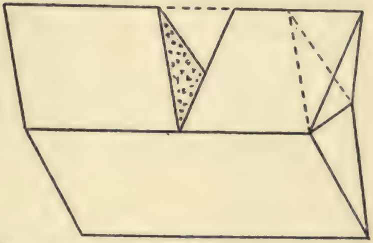

FIG. 93.—Baumhauer's experiment on the twinning of calcite (after Groth).

The experiment requires care, since the new twin-layer is liable to break away. There can be little doubt that the repeated twinning seen in granular calcite in rock-slices is due to stresses set up in the earth's crust while the crystalline grains are developing, or even long after the mass has crystallised.

Calcite twins of various types are well known to collectors, including scalenohedra twinned on the basal plane and the "butterfly" twins, where two prismatic individuals are united by the plane of a rhombohedron, giving rise to a knee-shaped form.

H. = 3. G. = 2·72. Calcite is frequent in veins, by itself or as a gangue for ores of lead and other metals. It forms the bulk of limestones, and, where the granular crystals are seen with the unaided eye, the rock is termed a "crystalline limestone." But every limestone is, in fact, crystalline, since amorphous calcium carbonate is unknown. Observation between crossed nicols shows that even the fibres of calcite in the shells of minute organisms, as well as the calcareous granules or cement in which they are embedded in a limestone, are crystalline, and they have been so from the date of their deposition. A large number of organisms, such as madreporarian corals and most bivalve shell-fish, make their hard parts of the rhombic form of calcium carbonate, aragonite; but the instability of this as compared with calcite renders calcite the prevalent mineral in "fossil" limestones. All echinoderms deposit calcite for their skeletons or tests, and each plate or spine of a sea-urchin, or each drum from the stem of a sea-lily, whatever its external and organic form, consists of one crystal of calcite. The molecules are thus orientated uniformly throughout such objects, and the cleavage of calcite is noticeable when they are found broken on rock-surfaces.

The relations of aragonite to calcite will be further discussed under aragonite. Calcite is essentially the form deposited from solution at temperatures below those of tropical surface-waters. The unstable calcium bicarbonate, $CaH_2(CO_3)_2$, in solution in river-waters may be brought to the sea in too great abundance on certain coasts. The saline water of the sea can only dissolve about 0·0191 % of $CaCO_3$, a figure rarely reached in the ocean. When, however, an excess is presented, precipitation of inorganic limestone takes place near shore, and this, in temperate climates, assumes the calcite form. Stalactites and the massive crusts in limestone-caves consist of calcite, often radial and distinctly crystalline in structure. The small stalactites of caves, or under arches where the mortar is attacked, sometimes cleave uniformly across, despite a central water-passage, showing that they consist really of one crystal.

Tests.—Effervesces freely in *cold* acids, unlike most mineral carbonates. Gives the flame of calcium. Distinguished best by its specific gravity from aragonite, and by Meigen's test (see Aragonite).

Opt.—Negative; refr. index $\omega = 1{\cdot}65849$, $\epsilon = 1{\cdot}48625$. Birefringence therefore very strong, $= 0{\cdot}17224$. Many of the optical characters and uses of calcite have been mentioned in Chapter VI, since the transparent crystals known as *Iceland Spar* have always served as the types of uniaxial minerals, and for the manufacture of Nicol's prisms. The strong double refraction causes all but very thin sections to give interference-colours of a high order, and almost white, between crossed nicols; it is, moreover, unnecessary to use thick sections to obtain the ring and black cross phenomena in convergent polarised light. Rock-forming calcite rarely shows crystal-outlines, being in this respect unlike dolomite. The granular forms are developed equally in veins and in massive limestones, and exhibit their cleavages excellently, and, between crossed nicols, their repeated lamellar twinning.

When the polariser alone is used, as in testing for axis-pleochroism, a striking difference of relief is seen, according to the position of the vibration-plane of the incident rays in relation to those of the crystal. When the rays vibrate in the direction for the ordinary rays, the relief is strong, owing to the considerable difference between the refractive indices of the balsam and the crystal for these rays; when the rays from the polariser vibrate in a plane perpendicular to this, they pass on in the crystal as extraordinary rays, the refractive index of the balsam for these being, of course, as before, about 1·540, while in the crystal the index may fall above or below this (1·486 to 1·658), giving the effect of relief, or may for some positions of the crystal coincide with this, when no relief at all will be apparent. Hence, on rapidly rotating the polariser below a section of calcite, a twinkling effect, due to the alternate appearance and disappearance of relief, is very often seen, which calls attention to the existence of the mineral in small grains and patches in an altered rock.[1] Dolomite will, of course, give a similar reaction, but is of rarer occurrence.

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[1] Good photographs illustrating this are given by T. Crook in Hatch and Rastall, "Petrology of Sedimentary Rocks" (1913), 390.

Aragonite. $CaCO_3$. — Colourless to white, grey, or brownish; transparent to translucent, with glassy lustre. Rhombic I. $a : b : c := 0{\cdot}623 : 1 : 0{\cdot}721$. Common form the prism {110} with angles 63° 48′ and 116° 12′, the brachypinacoid pair {010}, and the brachydome {011}; but the crystals are usually triplets, twinned on a prism-plane, and producing, by interpenetrant growth, the effect of a hexagonal prism with vertical notches down its sides (Figs. 94 and 95). Elongated crystals with acute pyramids such as {991} also occur, producing almost needle-like forms (Fig. 96). A curious aragonite aggregate,

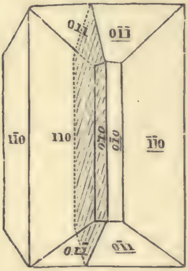

FIG. 94.—Crystal of aragonite, twinned on a prism plane.

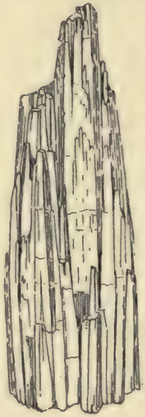

FIG. 96.—Aragonite, Frizington, Cumberland.

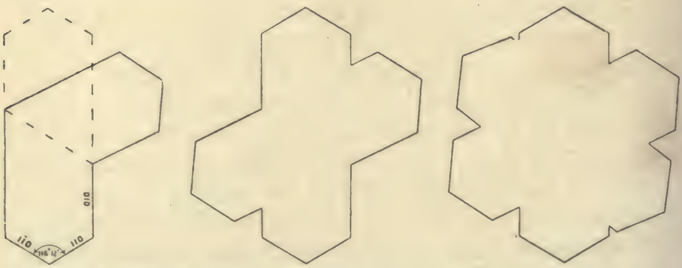

FIG. 95.—Horizontal sections of aragonite, to show the relation of the twinned form in Fig. 94 to the interpenetrant triplet form.

known as *flos ferri* from its association with iron ores, resembles white branching coral, with curving stems. Cleavage perfect brachypinacoidal. H. = 3·5—4. G. = 2·94.

Aragonite is unstable as compared with calcite, and more readily yields itself to replacement by dolomite or to solution in natural waters. In the course of time it passes into calcite, and in a few hours or days in the case of artificial precipitates. When this occurs in massive rocks, there is probably a loss of substance in solution; but A. R. Horwood and others[1] have shown that shells formed of aragonite may remain as such for long geological periods, and even from Jurassic times, if preserved in clays. In limestone the change seems much more rapid, while in sands they are often dissolved away. Almost all the reef-building and single corals at the present day form their hard parts of aragonite; this is true also of land-snails, and the vast majority of marine molluscan shells. Echinoderms, crustacea, and brachiopods, on the other hand, deposit calcite.[2]

Oolitic grains, as in the Great Salt Lake of Utah, and on tropical coasts, are formed of aragonite. They have, however, passed into calcite in the oolitic limestones that are so well known as building stones. Aragonite also arises when calcium carbonate is precipitated by ammonium carbonate from the calcium chloride and calcium sulphate in sea-water, a process that takes place where decaying organisms are abundant. This is independent of the temperature, and the calcite cement of many "fossil" shelly limestones may have originally been aragonite. In tropical climates, any excess of calcium bicarbonate (see under calcite) is thrown down in sea-water as aragonite.[3] Aragonite is always the form of $CaCO_3$ precipitated from boiling solutions, and occurs as a natural product of hot springs. J. D. Dana, in his "System of

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[1] For references see G. Cole and O. H. Little, "Mineral condition of calcium carbonate in fossil shells," *Geol. Mag.* (1911), 49.

[2] One of the most striking researches on this subject is by G. Rose, "Ueber die heteromorphen Zustände der kohlensauren Kalkerde," *Abhandl. Akad. Wiss. Berlin* (1858), 63.

[3] G. Linck, "Die Bildung der Oolithe u. Rogensteine," *Neues Jahrb. für Min.*, **16** (1903), 495.

Mineralogy," quotes a case in Nevada where aragonite is being laid down from mine-waters at 30°; at Příbram it forms crusts at ordinary temperatures, and such cases are no doubt due to chemical precipitation.[1]

If, following the classical observations of G. Rose,[2] we boil a solution of calcium chloride, and pour into it a hot solution of ammonium carbonate, aragonite is precipitated in minute fibrous branching forms, and also in beautiful six-rayed "rosettes," which appear to be true triplets, like those so well known in natural crystals. These triplets are plate-like through reduction of the *c*-axis, and the very weak birefringence (·004) for aragonite when viewed down this axis renders these minute forms practically isotropic. When inclined in the liquid to the direction of the rays from the polariser, they show interference-colours. In a week or so, if left in the liquid, the precipitated aragonite passes into calcite in rhombohedral forms. As remarked above, ammonium carbonate throws down calcium carbonate as aragonite, whether the solution is hot or cold. A solution of sodium carbonate added to one of calcium sulphate precipitates aragonite when boiling, but calcite when cold.[3] The calcite appears as a fibrous deposit at first, but develops rhombohedra in an hour or so.

Rose also pointed out that well-crystallised aragonite (not the minutely fibrous form in shells) passes into calcite at a red heat. The experiment may easily be repeated in a glass tube. The aragonite breaks up into spreading fibrous forms, which appear to retain the surfaces of the original particles where they represent part of the exterior. This product is white, and, as Rose showed, has a specific gravity of about 2·70. It no longer responds to Meigen's test for aragonite (see below), but may show in part a very faint blue tinge, probably from admixture of strontianite.

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[1] See F. Slavik, *Bull. Internat. Acad. Prague* (1912), 128.

[2] *Poggendorff's Annalen*, **42** (1837), 354, and *Abhandl. Akad. Wiss. Sci. Berlin* (1856), 8.

[3] See a series of experiments by W. Meigen, *Ber. naturforsch. Gesell. Freiburg i. Breisgau*, **15** (1907), 20.

Tests.—On heating to redness in a closed tube, splits up and passes into calcite in white fibrous forms, this white product being characteristic. Calcite merely decrepitates.

Behaves with acid and flame like calcite, but the specific gravity provides an unfailing distinguishing test. W. Meigen[1] has made discrimination still easier by showing that aragonite boiled in cobalt nitrate solution turns violet, through precipitation of basic cobalt carbonate, while calcite, unless powdered to altogether exceptional fineness, remains colourless. A standard solution[2] may be made by adding two volumes of water to one of a cold saturated aqueous solution of cobalt nitrate. Boil the fragments to be tested for three minutes. Chemically prepared tricalcium orthophosphate and the mineral witherite, $BaCO_3$, behave like aragonite; but apatite and phosphatised fossils give no reaction. Strontianite, $SrCO_3$, turns blue.

Aragonite behaves like calcite with Lemberg's test (see Dolomite, p. 221), but the pink colour is feeble.

Opt.—Negative; α-axis parallel to the vertical axis of the crystals. Refr. indices, $\alpha = 1·530$, $\beta = 1·681$, $\gamma = 1·685$. The birefringence thus varies very greatly in different sections, that containing the α-axis and the γ-axis showing high colours, while that containing the β and the γ axes will give pure tints like those of orthoclase. Most sections, when the polariser alone is used, will show the striking changes in relief described under Calcite.

Ktypeite, proposed as a name for the pisolitic mineral at Karlsbad, and *Conchite*, proposed for the material in most molluscan shells, have both again been merged in aragonite, since the differences in density and refractive index on which they were based have not been maintained.

WOLLASTONITE. $CaSiO_3$.—See Silicates, Pyroxene division.

PEROVSKITE. $CaTiO_3$.—Yellow to black. Cubic. H.=5·5. G. = 4·0. Occurs as lustrous grains and small crystals (octahedra and cubes) in ultrabasic and basic igneous rocks. When silica is more abundant, SPHENE, $CaTiSiO_5$, is commonly developed (see Silicates).

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[1] *Centralblatt für Min.* (1901), 577, and *Ber. naturforsch. Gesell. Freiburg i. Breisgau*, **15** (1907), 20.

[2] Cole and Little, *op. cit.* above, *Geol. Mag.* (1911), 52.

Apatite. $(CaF)Ca_4(PO_4)_3 = 3Ca(PO_4)_2.CaF_2$.—Tricalcium orthophosphate with calcium fluoride. Chlorine sometimes replaces the fluorine. CaO about 50 and P_2O_5 42 %. Colourless and transparent at times, sometimes blue; but larger crystals are more often opaque, and white, green, or reddish-brown. Lustre resinous rather than vitreous. Hexagonal III, isomorphous with pyromorphite; $a : c = 1 : 0{\cdot}7346$. Common forms hexagonal prism with bipyramid of first order and basal pinacoid. Sometimes third order bipyramid planes occur, indicating the true symmetry (Fig. 39). Often massive. H. = 5. G. = 3·2.

Occurs in minute crystals, separated out at an early stage in igneous rocks, notably in diorites and dolerites, and included in the other minerals. On decay of such rocks, the apatite no doubt becomes a soil-mineral, and contributes, on its slow solution in acidulated water, the phosphorus so much needed by plants. Apatite occurs also in coarse masses in igneous veins. In eastern Canada, as at South Burgess, crystals 20 cm. or more in diameter occur in a matrix of calcite, in which they have developed as doubly terminated prisms. Here the material seems to have been brought into place by mineral springs. Concretionary calcium phosphate, with approximately the composition of apatite, occurs in many places, and replaces or forms casts of fossil remains. Such massive types may be generally styled *phosphorite*, and, like apatite in general, are much sought after as agricultural fertilisers. It seems likely[1] that the dark grey concretions of Podolia in S. Russia, which resemble old-fashioned cannon-balls, include DAHLLITE, $3Ca_3(PO_4)_2.CaCO_3$, which is isomorphous with apatite. Where fossil bones have accumulated, nodular calcium phosphate arises in time, and the removal of calcium carbonate from the bones that survive leaves them rich in phosphate. Such materials, including both altered bones and nodules, have a characteristic yellow-brown to deep brown colour, with a high glaze. The small brown phosphatic concretions that occur in marine rocks, as in the chalk of southern Belgium and northern France, are no doubt original to these deposits and are paralleled by materials in calcareous and glauconitic oozes at the present day. Recent foraminiferal shells have been found, not only infilled, but actually replaced by calcium phosphate.[1]

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[1] A. F. Rogers, "Dahllite (Podolite), &c.," *Amer. Journ. Sci.*, **33** (1912), 475.

The phosphorite of the Cambridge Greensand, of the Potton and Upware Beds in Bedfordshire, and of the Suffolk "bone bed," consists of casts of fossils associated with bones and lumpy concretions, largely derived from earlier formations. The Eocene phosphate beds of South Carolina contain abundant sharks' teeth and mammalian bones. Inarticulate brachiopods are believed to have originated phosphorite beds in the Bala horizon of the Ordovician of N. Wales. *Coprolites*, the excreta of fish or marine reptiles, are occasionally recognisable as sources of phosphorite.

Where limestones are associated with phosphatic deposits, as in the Quercy region of the Jurassic beds in south-central France, it is often difficult to say whether the phosphate is original, or whether it is due to infiltration and replacement. Where, however, as in the lowest Eocene strata of the Atlas ranges of Algeria and southern Tunisia (" Gafsa phosphate," etc.), the phosphatic limestones recur over a wide area in the same stratigraphical series, it is clear that they were developed under local conditions contemporaneously with the deposition of the strata. *Guanos*, formed from the excreta of birds on rock-shelves, especially on islands, pass into phosphorite, and coral or other limestone masses below them often become phosphatised by infiltration. The most valuable guanos are those that have retained their ammonium salts; ammonium oxalate and carbonate react on the calcium phosphate, and produce the very soluble ammonium phosphate.

Phosphorites with 50 to 75% of $Ca_3(PO_4)_2$, that is, about 23 to 34 % of P_2O_5, are at present profitable for working.

Tests.—Small crystals, even in a thin slice, which can be uncovered and cleaned from balsam for the purpose, readily give a yellow precipitate with a nitric acid solution of ammonium molybdate. The flame-test, when the specimen is moistened with H_2SO_4, shows the yellow-red colour due to calcium and the green due to phosphorus beyond it. If any doubt remains as to the phosphorus, it is always well to fuse 4 mm. or so of magnesium tape with the powdered mineral in a closed tube. When cool, add a drop of water; the smell of hydrogen phosphide, PH_3, is at once recognisable. Apatite gives no reaction when boiled in cobalt nitrate, though chemically prepared $Ca_3(PO_4)_2$ turns violet. Apatite dissolves in HCl and NHO_3, and with H_2SO_4 gives a white precipitate of $CaSO_4$. The specific gravity is a useful character.

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[1] Murray and Renard, "Deep Sea Deposits," *Challenger Reports* (1891), 391.

Opt.—Negative. Refr. index, $\omega = 1{\cdot}638$, $\epsilon = 1{\cdot}634$.[1] Birefringence therefore weak, 0·004. Interference-colours lower than those of quartz. The relief and the well-developed crystalline form distinguish it, however, from quartz in igneous rocks; hexagonal cross-sections are frequently seen. Colourless in thin sections.

NITROCALCITE. $CaN_2O_6 \cdot nH_2O$.—Calcium nitrate occurs in this form as colourless crystals in dry soils, and is originally produced by the action of nitrifying bacteria on salts of calcium. Deliquescent.

ANHYDRITE. $CaSO_4$.—White, grey-blue. Rhombic I. Usually massive, and like a crystalline limestone. H. = 3—3·5. G. = 2·9. Occurs as beds in old lake-areas, with gypsum and rock-salt. It results in many cases from the dehydration of gypsum in geological time. It may again take up infiltering water and pass into gypsum.

Gypsum. $CaSO_4 \cdot 2H_2O$.—Colourless and transparent (*Selenite* type) to whitish and translucent. Monoclinic I. Highly characteristic form the prism {110}, the clinopinacoid pair {010} and a "negative" hemibipyramid {111} (Fig. 97). The planes of this last form might of course have been treated as a clinodome; the angle between the *a* and *c* axes, however, on the accepted reading, is 80° 42′.

The crystal is so read that the planes making the less obtuse interfacial angle, 111° 30′, are the prism-planes; the angle between $(1\bar{1}1)$ and (111) is 143° 48′. Twinning on (100) common, producing "arrow-head" forms (Fig. 98); the resemblance to a barbed arrow or lance head is more marked through the frequent curvature of the prism and pyramid planes. Cleavage perfect, clinopinacoidal. The cleavage-flakes are slightly flexible, but not elastic. H. = 2. G. = 2·3.

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[1] For range of variation, see Iddings, "Rock Minerals" (1911), 523.

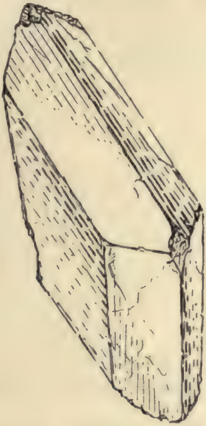

FIG. 97.—Gypsum (Selenite).

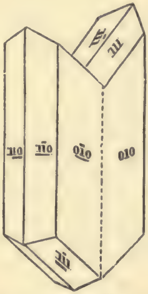

FIG. 98.—Twin-crystal of gypsum.

Gypsum occurs as well-developed crystals in clays, and often results from the action of decomposing iron pyrites upon the calcium carbonate of fossil shells. But as a rock-former it is conspicuous in massive beds as the product of the evaporation of lakes in arid areas. In the western states of N. America it is still developing in the soils as the result of the constant evaporation of capillary water, and crystal-groups form the "stars of the desert" on the surface of dry lands in the interior of Algeria.

Masses of crystalline granular gypsum are known as *alabaster*. They are sometimes veined with brown iron oxide, and are used for carved ornamental work for the interior of buildings. The solubility of gypsum in 400 parts of water renders it quite unsuited for external decoration.

Under the name of *land-plaster*, gypsum has been used since the eighteenth century to supply lime to the soil, and to ameliorate the texture of clayey lands. It forms an excellent but somewhat expensive corrective for alkali-soils, since the deleterious sodium carbonate may be converted by its means into harmless sodium sulphate, while the extremely close texture produced by the "black alkali" in clay-soils is destroyed (see p. 244).

Fibrous gypsum, known as *satin spar*, has a beautiful silky lustre, and is worked into ornaments.

Tests.—Gives off water in the closed tube and becomes white and dull. The sulphur must be looked for on reduction with the silver coin test. The fact that gypsum can be scratched with the thumb-nail easily distinguishes it from calcite.

Opt.—Rarely seen in rock-slices. Refr. indices, $\alpha = 1{\cdot}520$, $\beta = 1{\cdot}522$, $\gamma = 1{\cdot}529$. Low relief. Birefringence weak, pure interference-colours resulting, which are vivid if a cleavage-plate is examined of greater thickness than an ordinary rock-slice. Optic axial plane (010), with inclined dispersion, at ordinary temperatures; but, as Eilhert Mitscherlich showed, it is perpendicular to (010) at 120°, the axes now showing horizontal dispersion. At intervening temperatures, gypsum becomes uniaxial, first for blue, then for green, yellow,[1] and red light; when the optic axial angle has thus become 0° for red light, the axes for blue light have opened out upon the second optic axial plane.

SCHEELITE. $CaWO_4$.—Colourless. Vitreous to adamantine lustre. Tetragonal III, isomorphous with stolzite. Sometimes massive. H. = 4·5—5. G. = 6. Common as an associate of cassiterite, topaz, wolfram, etc., in tin-bearing veins, and is mined in Otago as a source of tungsten.

Tests.—The specific gravity calls attention to it in massive forms, and the blowpipe-tests at once distinguish it from cerussite or anglesite, two other heavy colourless minerals. Gives a clear sapphire-blue bead in R.F. with microcosmic salt (tungsten reaction); colourless bead in O.F.

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[1] A. Hutchinson and A. Tutton show that the temperature at which gypsum is uniaxial for yellow light is 90·9°; *Min. Mag.*, **16** (1912), 257.

Zinc.

The minerals of the zinc series readily give the white oxide on charcoal; this sometimes forms best when they themselves are undergoing reduction in R.F. The oxide turns a bright yellow-green after moistening with cobalt nitrate and strongly reheating in O.F. No metallic bead, since the metal volatilises.

Zinc-Blende (Blende; Sphalerite). ZnS. Zn 67 %.—Translucent and even transparent; yellow-brown to black ("Black Jack" of miners). Resinous to vitreous lustre. Cubic III, showing rhombic dodecahedron, cube, and sometimes tetrahedral forms. Cleavage perfect (110), so that there are six equivalent cleavage-directions, making angles of 120° with one another, or 90° when two cleavages are selected from the same zone of the rhombic dodecahedron. H. = 3·5—4. G. = 4.

A very common ore, associated with galena in all lead mines. Sometimes massive; the dark varieties contain iron, and traces of cadmium are usually present.

Tests.—Fusibility very high (about 6). The sulphur is best recognised by the test on a silver coin after reduction. Soluble with effervescence in hot HCl, with evolution of H_2S.

WURTZITE. $(Zn,Fe)S$.—Brown and commonly fibrous. Hexagonal II; crystals rare, but isomorphous with greenockite, CdS. Formerly regarded as fibrous zinc-blende.

ZINCITE. ZnO. Zn 80 %.—Rich red, with orange streak. Vareties with much MnO are yellower than the more pure mineral. Hexagonal II. Strong basal cleavage. Commonly massive, and very rare except at Franklin Furnace in New Jersey. H. = 4·5. G. = 5·5.

The **Calamines**, or white zinc ores. Since both the carbonate and the hydrous silicates of zinc have secured the name of calamine, originally given to the latter by Brongniart in 1807, it seems well to adopt the French compromise, and to speak of both these light-coloured ores as calamine ores. The original name of the carbonate, known as calamine to the English trade, was Smithsonite, given to it by Beudant in 1832.

Smithsonite. $ZnCO_3$. Zn 52%.—Translucent grey to white; often yellow-green. Trigonal IV, the unit rhombohedron having the angle over its polar edges 107° 40′. $a : c = 1 : 0·8062$. Crystals rare; commonly massive, and often mammillated, as an encrustation in veins. H. = 5. G. = 4·45.

Frequently an alteration-product of zinc-blende. Replaces beds of limestone or dolomite, as at Santander in Spain.

Hemimorphite (the original Calamine). $Zn_2SiO_4 . H_2O$. Zn 54%.—This is so commonly associated with smithsonite as an ore that is dealt with here. Much like smithsonite, with a tendency towards blue rather than green tints when coloured. Rhombic IV, the frequent small colourless crystals serving as a type of rhombic hemimorphism (Fig. 19). The vertical direction becomes electrically polar on heating, whence the mineral is often called *electric calamine*.

Tests.—Often effervesces in hot HCl, owing to formation of smithsonite; but yields gelatinous silica.

WILLEMITE, Zn_2SiO_4, is trigonal V, nearly isomorphous with phenacite, Be_2SiO_4. White to yellowish, often impure and limonite-brown. Gelatinises when boiled in HCl, like hemimorphite, but pure varieties do not give off water in the closed tube.

TROOSTITE is a manganiferous willemite.

Cadmium.

Cadmium forms a brown encrustation, thinning out to yellow, when the mineral is reduced on charcoal with sodium carbonate. This encrustation sometimes appears during the reduction of zinc-blende, which often contains cadmium.

GREENOCKITE. CdS.—Rare, usually appearing as yellow crusts in zinc localities. Hexagonal II, isomorphous with wurtzite.

Strontium.

The crimson flame is stronger in strontium than in calcium minerals. When the mineral is dissolved in HCl and diluted greatly with water, a white precipitate of $SrSO_4$ is still produced on the addition of a drop of H_2SO_4. Calcium salts give no precipitate, owing to the solubility of calcium sulphate in water.

STRONTIANITE. $SrCO_3$.—Colourless, greenish, yellow-brown. Rhombic I, fairly isomorphous with aragonite. Often in radial massive groups. H. = 3·5—4. G. = 3·7. This high specific gravity should be noted. Turns blue when boiled with cobalt nitrate.

CELESTINE. $SrSO_4$.—Colourless, white, or faintly bluish. Rhombic I; forms near those of anglesite and barytes. $a : b : c = 0{\cdot}779 : 1 : 1{\cdot}280$. The crystals are read commonly as tables, with well-developed basal pinacoids. Domes frequent, the prism {110} appearing as small kite-shaped planes on the lateral angles. In radial groups, the brachydome {011} appears at the free ends of the crystals, forming gables. H. = 3—3·5. G. = 3·96, a useful character. Common with sulphur in Sicily, and in hollows of limestone near Bristol.

Barium.

The yellow-green flame is characteristic, and is well seen when the powdered mineral is thrown through the colourless flame of a Bunsen burner.

WITHERITE. $BaCO_3$.—Colourless, white, or greenish. Rhombic I, isomorphous with strontianite and cerussite, but crystallising in triplets, which resemble hexagonal bipyramids. H. = 3·5. G. = 4·3, higher than that of strontianite. Turns violet, like aragonite, when boiled with cobalt nitrate.

Barytes (Heavy Spar). $BaSO_4$.—Colourless and transparent to white and opaque. Often yellow-brown. Rhombic I; $a : b : c = 0{\cdot}815 : 1 : 1{\cdot}314$. Crystals are orientated as those of celestine, the broad pinacoid pair being taken as basal planes. Crystals from Felsöbanya in Hungary show merely the basal planes and the prism, which has an angle of 78° 22′. Perfect basal cleavage, also prismatic cleavage; hence the cleavage-form reproduces the Felsöbanya crystals. H. = 3. G. = 4·5. Common in veins, resembling calcite, and as a cement to sandstones.

Tests.—The specific gravity readily distinguishes it from other white cleavable veinstones. Barium flame; the silver coin test reveals sulphur.

Mercury.

NATIVE MERCURY is occasionally found in cavities in cinnabar, when the mineral is broken, and in geodes of quartz in the Californian mercury area. It occurs as liquid globules in most mercury mines, and is seen to be carried along in suspension in springs in Galicia and Transylvania, passing thus into the alluvial state. G. when liquid = 13·5. Cubic on solidification at —38·8° C., with G. = 14·2; malleable.

Cinnabar. HgS. Hg 86%.—Vermilion to purple-red and almost black. Streak vermilion. Trigonal VI, like quartz, and showing rotatory polarisation. H. = 2·5, like that of the red silver ores; but G. as high as 8. The one important ore of mercury.

Tests.—Completely volatile in closed tube, giving a deep red or black sublimate, which is vermilion when scratched. With sodium carbonate in the tube, deposits metallic mercury.

Radium.

The geological importance of radium is referred to on p. 149 and also under Uranium, from which element it appears to be derived as a member of an evolutionary series. The metal itself was isolated in 1910. The energy manifested during the transformation of radium is a considerable source of heat within the earth.

CHAPTER XIV

GROUP I, INCLUDING HYDROGEN, SODIUM, POTASSIUM, AND COPPER

Hydrogen.

Water (Ice). H_2O.—Like mercury, a liquid mineral at ordinary temperatures; it forms, however, a crystalline solid below 0°, a temperature frequently reached on the earth's surface, and realised throughout the year above the snow-level in the atmosphere and in large areas near the north and south poles. Hexagonal. In lake-ice, prismatic crystals form with their basal planes parallel to the surface; these crystals may be a foot or more across, and meet along irregular boundaries. In glacier-ice, which is generated from the growth of granular crystals in the *névé* or *firn* of snowfields, the crystals have no regular form, but each "glacier-grain" is a single crystal. These grains may measure from 2 to 150 mm. in diameter. Ice-crystals have gliding planes perpendicular to their principal axes, and pressure in this direction produces deformation. Individual crystals are thus forced out of shape in glaciers, and this contributes considerably to glacier-movement. At their surfaces, moreover, the granular crystals are liable to melt under pressure, since ice occupies a greater space than the corresponding weight of water; the grains slide over one another, but consolidation again occurs as the pressure is relieved. *Regelation* then sets in, the new ice fitting itself in crystallographic continuity on the surface of one or other of the adjacent grains. Crystalline grains in glaciers are thus able to transfer molecules to one another; they increase in size towards the lower end of the ice-stream. The irregular interlocking boundaries of the glacier-grains are well seen as the ice is melting. Ice has H. = 1·5. G. = 0·9167. At 0°, 100 gr. of liquid water occupy 100·012 c.c., a slight expansion from 100 c.c. having taken place during the reduction of the temperature from that of maximum density, 4°, or strictly 3·945°. At 0° this water passes into the crystalline form, ice, and occupies 108·992 c.c., the suddenness of the final expansion amounting to nearly nine per cent., and sufficing to burst vessels in which the water is confined. Water in the crevices of rocks thus becomes a powerful geological agent of disintegration in climates that allow of alternate thaw and frost.

Snow-flakes are composed of aggregates of minute crystals of ice, which are mostly skeleton-forms. The rapidly deposited crystals in *hoar-frost* are similarly skeletal, and build up feathery aggregates. Both these types represent deposition from vapour, akin to the sublimates procurable, at appropriate temperatures, from other minerals. *Hail*, on the other hand, results from the consolidation of liquid water, and hailstones are ice-spherulites, showing concentric and also radial structure. Conical hailstones occasionally fall, which cannot be regarded merely as fragments of stones possessing radial structure.

The permeation of all rocks by water, and the probability that the earth is still giving off nascent or "juvenile" water that was occluded at the time of the consolidation of its crust, makes this oxide of exceptional geological interest and importance. As a solvent and a transporting agent, it plays a fundamental part in the formation of mineral veins, while at the surface its mobility and power of dissolving acids, which react upon the rocks, render it one of the chief agents of denudation. Its gravitational flow even in the solid form enables it to wear away the floors and walls of valleys, and to transport enormous quantities of loose material. Hence water provides us, not only with a river-alluvium, but with an ice-alluvium also, where glaciers of the broad continental type have melted and left their impurities behind.

Sodium.

Rock-Salt (Halite). NaCl.—Colourless to brown or even blue. Cubic IV, the absence of planes of symmetry being revealed by corrosion-figures. Common as cubes; cleavages parallel to {100} (Fig. 99). H. = 2—2·5. G. = 2·4; but this cannot be determined in water.

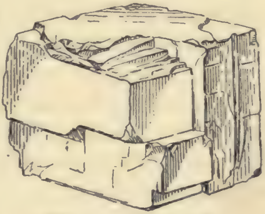

FIG. 99.—Rock-salt.

The deliquescence of many specimens is due to the presence of $CaCl_2$, $MgCl_2$, and $MgSO_4$. Soluble in water. The taste is well known, but does not distinguish rock-salt from the far rarer sylvine. Occurs occasionally as crusts on soils, but usually in large beds, in places 100 feet or more in thickness. These may be traced to the evaporation of ancient lakes or lagoons. The deposition of sodium chloride may be observed in modern instances, as in the Dead Sea and in Sevier Lake in the Utah Basin, the latter occasionally drying up until even calcium and magnesium chloride appear on the surface. In many places, by successive washing of the sea across sand-bars, evaporating lagoons behind these barriers are converted into extremely saline lakes, and the sand or mud on their margins becomes charged with crystals of rock-salt.

As a lake evaporates, any calcium carbonate becomes thrown down first, as oolitic grains upon the shores or as encrusting calc-tufa or travertine; then the sulphate follows, taking up some of the water also and appearing as gypsum; then, unless "fresh" water returns to the area, the sodium chloride makes its appearance.

The features of the salt-lakes of the present day are repeated among the continental deposits of Permian and Triassic age in north-west Europe, and successive beds of gypsum and rock-salt record the fluctuations in the salinity of the waters.

Rock-salt may be mined by excavating in the bed itself, leaving a roof perhaps forty feet thick, and hollowing out vast chambers, which need few pillars for support. If the land above is not too valuable, the salt of the roof and of small beds can ultimately be extracted as brine with water. This usually causes sinkings of the surface, as may be seen near Droitwich, and lakelets in some districts are ascribed to the removal of salt and gypsum from below by natural waters.

The immense quantity of sodium chloride blown from the surface of the oceans supplies sufficient sodium to soils far removed from the margins of the continents. T. H. Holland, as the result of quantitative experiments, has urged that the rock-salt of Panjab may have accumulated in the dry interior of the country from salt borne by wind blowing over the flats on the west shore. J. Joly has utilised the sodium chloride stored in the oceans, as compared with that brought down by rivers from the land, as a measure of geological time.[1]

Tests.—The mineral should be tasted. The chlorine is well revealed by the test with copper in a bead of microcosmic salt.

CRYOLITE, the fluoride of aluminium and sodium, has been described already under Aluminium (p. 214).

THERMONATRITE, $Na_2CO_3 . H_2O$, forms a white efflorescence on the soils of arid regions. TRONA, $Na_2CO_3 . HNaCO_3 . 2H_2O$ occurs similarly, and in Churchill Co., Nevada, forms a massive bed. All forms of sodium carbonate are highly deleterious to plant life, and the dark products formed by them with humus in the soils have caused the name "black alkali" to be applied to them. Not only do they injure the vegetation, but they deflocculate the soil, keeping it in a permanently finely divided state. Gypsum has been applied to "alkali-soils" to convert the sodium carbonate into the innocuous sulphate; this process is usually too costly, and prolonged washing by irrigation, with effective drainage at the same time, seems the only remedy.

SODA-NITRE (CHILE NITRE, CHILE SALTPETRE). $NaNO_3$. N 16·47 %.—Colourless or white. Trigonal IV, with forms near those of calcite. Occurs in arid areas as crusts, layers, or diffused crystals in the soil. The great source is the desert of Tarapaca in northern Chile, where it occurs in beds styled *caliche*, with rock-salt, potassium iodide and iodate, and sodium sulphate. Caliche is a Spanish term for lumpy impurities in bricks. The bed is at times six feet thick, lying beneath a gypsum-bearing gravel, and contains 20 to 50% of soda-nitre.

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[1] See T. H. Holland, "The Origin of Desert Salt-deposits," *Proc. Liverpool Geol. Soc.*, **9** (1912), 227.

The substances associated with the Chile nitrate have suggested a marine origin; but it is far more probable that all the compounds have been brought by waters from a distance, and have accumulated by capillary action and evaporation in the upper layers of the desert soil. Bacterial action, perhaps on the flanks of the Andes, has produced nitric acid, and this has formed the sodium salt.[1] By refinement on the spot, a product is secured containing 14 to 16% of nitrogen, which is the substance wanted by the agriculturist. Soda-nitre was first imported into England about 1838, and is now one of the most important fertilisers.[2]

Tests.—Soluble in water. Deflagrates when heated on charcoal, giving a strong sodium flame.

BORAX, $Na_2B_4O_7.10H_2O$, is another colourless to white product of salt-lake areas. Monoclinic I (Fig. 16).

Tests.—Soluble in water. Taste sweetish. Intumesces in the flame before fusion; with H_2SO_4 gives a green boron flame.

Potassium.

The blowpipe-test for potassium depends on the pink-violet colouration of the flame. The common occurrence of sodium, in or on the surface of the mineral, commonly masks this to the unaided eye; and the blue glass provided in laboratories or by dealers is usually too thin to cut off the luminous sodium flame or even that of a blowpipe-lamp. Such flames appear violet through *thin* commercial blue glass, and resemble that due to potassium. If, however, two or three pieces of blue glass are superposed, so as to give a thickness of 5 mm., as described on p. 160, a bright luminous flame may still show through, but will appear blue, while any potassium present will give a pink-violet colour. This reaction is best practised with a Bunsen burner. In the case of silicates, it is well to fuse the mineral granules in a bead of sodium carbonate and to heat this in the flame. Thorough decomposition is thus secured.[1] The bead may be fused, dipped in HCl, and then replaced in the flame.

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[1] For a general review of the processes by which nitrogen is thus fixed in soils, see E. J. Russell, "Soil Conditions and Plant Growth" (1912), 90.

[2] See Penrose, "Nitrate deposits of Chile," *Journ. Geol.*, **18**, 1; and Mayer, "Agrikulturchemie," **2** (2), 144.

SYLVINE. KCl. K 52·46 %.—Colourless and transparent; resembles rock-salt. Cubic IV, as revealed by corrosion-figures. Perfect cleavage parallel to cube-planes. H. = 2. G. = 2. Occurs in salt mines, but not in considerable masses. In the Stassfurt area, in Anhalt, a mixture of sylvine and rock-salt is sold as "sylvinite," and contains some 26 % of sylvine.

Tests.—Soluble in water; tastes like rock-salt. Potassium flame; shows the chlorine with copper in microcosmic salt.

CARNALLITE. $KCl.MgCl_2.6H_2O$. K 14·1 %.—Colourless, or reddish when stained with iron. Rhombic. Deliquescent; soluble in water. In the Stassfurt area, overlies the kieserite bed, as one of the last products of the evaporating lakes. Largely in demand as a fertiliser.

KAINITE. $KCl.MgSO_4.3H_2O$. K 15·7 %.—Monoclinic. Not deliquescent. Soluble in water. In the Stassfurt area, occurs as an extension of the carnallite bed, from which it has probably been derived by the introduction of $MgSO_4$ from the kieserite below, through the action of subterranean waters. Sea-water infiltering from above may also have contributed the sulphate. Largely in demand as a fertiliser, and has been widely used in a crude form, under the German name of "kainit."

The agricultural possibilities of the *potash-salts* of Stassfurt were recognised about 1865, and the most modern tendency is to convert them into potassium chloride or sulphate on the spot. For commercial purposes, the potassium content is usually calculated as potash, which, after all, is fairly expressive, since 83 % of K_2O consists of potassium. The following table may be useful (compare L. A. Groth, "The Potash Salts" (1902), 96):—

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[1] G. Cole, "Potassium in Silicates," *Geol. Mag.* (1898), 103.

TABLE OF PERCENTAGES.

	Pure mineral.			Commercial.	
	KCl	K	Stated as K_2O	KCl	Stated as K_2O
Carnallite	26·8	14·1	17	15–20	9·8
Kainite	30	15·7	18·9	20	13
Sylvine	100	52·4	63	—	—
"Sylvinite"	—	—	—	26·3	17

The potash-salts and associated minerals of western Prussia have been elaborately investigated and reproduced in a series of researches by van't Hoff and his pupils in the University of Berlin. Several of these salts are not formed artificially at temperatures below 25° (77° F.); but Ochsenius[1] has pointed out that this temperature may be reached on the floors of shallow lagoons in a warm climate, such as no doubt prevailed in Europe during the desiccation of the Stassfurt lakes.

NITRE. KNO_3.—Colourless. Rhombic. H. = 2. G. = 2·1. Occurs in thin tufts and crusts, and as an efflorescence, in the soils of arid lands; in other cases it may appear on the surface as the water dries up after rain. The plains of Bengal produce a large part of the native mineral, which is in such demand for the manufacture of gunpowder that it finds no place as an agricultural fertiliser. It is more economical to use soda-nitre and a "potash-salt" on the fields than to supply both the required ingredients together in the form of nitre.

Nitre no doubt is mainly formed through bacterial action. In India it accumulates especially in the neighbourhood of villages, where waste nitrogenous products can be broken up, the nitrogen becoming fixed with potash in the soil.

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[1] *Zeitschr. für prakt. Geol.* (1905), 167. On possible temperature and volume changes subsequent to deposition, see S. Arrhenius and R. Lachmann, *Geol. Rundschau*, **3** (1912), 139.

Tests.—Soluble in water. Deflagrates when heated on charcoal even more strongly than soda-nitre. Potassium flame.

Copper.

The bright green flame due to copper, and especially the blue flame due to the chloride when the mineral is moistened with HCl, are obtained with such small traces of copper that it is always well, in estimating the importance of copper in a mineral, to try and reduce the mineral to metal. Copper pyrites presents some difficulty in this respect. The colours with fluxes are best seen in microcosmic salt, and the opaque red in R.F. is much more recognisable in the yellow light of a lamp or of a gas-burner than in daylight.

Native Copper.—Characteristic metallic red, but darkened on the surface. Cubic; usually dendritic or leafy, forming sheets in crevices of veins, but sometimes in very large masses. Such masses cannot be blasted, but must be hewn away, owing to the toughness and ductility of the metal. H. = 2·5–3. G. = 8·8. Common in all copper mines, and is the main ore in the Lake Superior region, where a mass has been found forty-five feet long and weighing 420 tons.

Tests.—Cut the surface with a knife to reveal the characteristic colour.

CHALCOSINE (CHALCOCITE; COPPER GLANCE). Cu_2S. Cu 79·85 %.—Blackish lead-grey. Sectile. Rhombic I. Crystals often tabular, the angles being sharp over the horizontal edges, where faces of the low bipyramid {113} meet. H. = 3. G = 5·7.

Tests.—Gives no S in the closed tube, but SO_2 in the open tube.

Copper Pyrites (Chalcopyrite). $CuFeS_2$ (possibly = $Cu_2S.Fe_2S_3$, which resembles the formula that may be assigned to bornite and tetrahedrite). Cu about 33 %.—The presence of iron must be borne in mind, since the name suggests a copper sulphide on the lines of iron pyrites. Greenish brass-yellow, tarnishing to orange, and sometimes covered with a brilliant iridescent film (*peacock copper ore*). Streak greenish black. Tetragonal VI, the characteristic bisphenoids being very nearly tetrahedra, since $a : c = 1 : 1{\cdot}0985$. Very common as a massive ore. H. = 3·5. G. = 4·2.

Copper pyrites must be distinguished in the field from the far less valuable iron pyrites; the two minerals are often in association. Copper pyrites is by far the most widely distributed ore of copper.

Tests.—The hardness, rendering it easily scratched with a knife, at once distinguishes it from pyrite or marcasite. Gives no sulphur in the closed tube. The reduction to metal is slow, and is best performed by roasting off the sulphur from a fragment by prolonged fusion in O.F. The globular residue, which is magnetic, may then be well treated in R.F., the copper finally separating from the iron, and showing as bright malleable metallic red beads when the mass is crushed on an anvil. The black powder associated with these beads is magnetic (Fe_3O_4). The bead in borax in O.F. is distinctly green and not blue, owing to the presence of the iron. The mineral is soluble in nitric acid, and possesses none of the malleability of gold.

ERUBESCITE (BORNITE). Cu_3FeS_3 (possibly $= 3Cu_2S.Fe_2S_3$). Cu about 60 %.—Purple to copper-brown on the tarnished surface, but bronze-yellow on freshly fractured surfaces. These tarnish in an hour or two, and hence the purplish tints are characteristic. Cubic I, but commonly massive. H. = 3. G. = 5. A valuable ore, and the principal one in some of the mines in Chile.

Tests.—Fuses to a magnetic globule, from which the copper is more readily extracted with sodium carbonate than is the case with copper pyrites.

TETRAHEDRITE (FAHLORE; GREY COPPER ORE). $Cu_6Sb_2S_6$[1] (possibly $= 3Cu_2S.Sb_2S_3$).—Silver replaces some of the copper, and arsenic replaces some of the antimony (see

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[1] Prior and Spencer, *Min. Mag.*, **12** (1899), 202.

Tennantite). Cu about 35 %, when Ag is about 8 %; when very little silver is present, Cu = 40 %. Grey to black, metallic lustre; in rare cases translucent, with a fine red tint. Cubic III, affording some of the most beautiful examples of the various tetrahedral forms and combinations. Crystals common and characteristic; but also occurs massive as an ore. H. = 4. G. = about 4·8. Silver is extracted commercially from tetrahedrite. Some varieties contain as much as 17 % of mercury.

Tests.—The silver may be found by careful cupellation after the copper has been oxidised away on the bone-ash. See Galena.

TENNANTITE. $Cu_6As_2S_6$ (compare Tetrahedrite; a series opens with the antimonial form and closes with pure tennantite).—The blowpipe-reactions serve to distinguish the two extremes.

ATACAMITE. $Cu_2ClH_3O_3$ ($= CuCl_2.3Cu(OH)_2$).—Bright green to dark green. Rhombic; usually fibrous and radiating. Occurs in the sands of Atacama, and is common with malachite in Chile.

Tests.—Is distinguished from the numerous other green ores of copper by burning in the blowpipe-tests with a luminous yellow flame, at the same time giving the blue of copper chloride close to the assay and the green flame beyond it. Sublimes in the closed tube, giving off water and yielding a grey deposit.

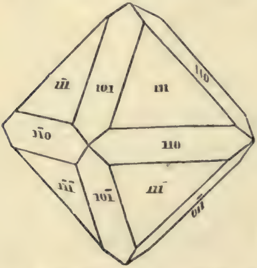

FIG. 100.—Crystal of cuprite, with octahedron and rhombic dodecahedron.

Cuprite. Cu_2O. Cu 88·8 %.—Deep red, with a hæmatite-red streak. Sometimes translucent, but commonly dark and opaque with an almost metallic lustre. Sometimes green on surface, through formation of malachite. Cubic IV, but usually exhibiting octahedral types of crystal consisting of combinations of forms occurring also in Class I, such as {111}, {110}, {100}, &c. (Fig. 100). *Chalcotrichite* is a translucent red capillary variety in which the rods consist of cubes greatly elongated along one axis. H. = 3·5—4. G. = 6.

A common ore, often associated with native copper. Octahedral crystals are commonly seen.

Tests.—Easily distinguished by blowpipe-tests from cinnabar, hæmatite, and the red silver ores. Reduced very easily to metal.

TENORITE (MELACONITE), CuO, is iron-grey, usually massive or earthy. Found in many copper mines. Crystals in the cavities of Vesuvian lava show the system adopted to be triclinic.

Malachite. $CuCO_3.Cu(OH)_2$. Cu 57·45 %.—Bright green, commonly opaque and dull. Monoclinic, but crystals rare. Usually encrusting and mammillated, as a stalagmite, on the walls of veins or on the surface of other copper ores. H. = 3·5—4. G. = 4. The commonest green copper ore. At Chessy on the upper Loire forms pseudomorphs of cuprite crystals. The massive blocks from the Urals are used as a very costly ornamental stone.

Tests.—Dissolves with effervescence in hot HCl. Very easily reduced to metal. Must be distinguished from the numerous green arsenates and phosphates.

AZURITE (CHESSYLITE). $2CuCO_3.Cu(OH)_2$. Cu 55·26 %.—Dark blue and translucent, with vitreous lustre, in crystals, to pale blue in powdery crusts. Monoclinic; crystals common, the prism and basal planes being conspicuous. Prism-angle 99° 32′. H. and G. as in malachite. Sometimes occurs in alternating crusts with malachite, in coarsely spherulitic forms.

DIOPTASE. H_2CuSiO_4.—Rich green and transparent. Vitreous lustre. Trigonal V, with third order rhombohedra modifying a combination of the second order hexagonal prism and first order rhombohedron. H. = 5. G. = 3·3.

A rare mineral, but possibly the crystallised representative of the far more common chrysocolla.

Tests.—Infusible. When boiled in HCl, yields a silica jelly.

Chrysocolla. $H_2CuSiO_4.H_2O$ (Groth).—Groth suggests that this mineral is a mixture of dioptase with opal. Bluish-green of various tints, opaque, with vitreous lustre. H. = 2—4.

G. = 2·2. A common ore in Cornwall and Chile, occurring massive and in crusts. Crystals are very rare, but are said to be identical with dioptase; the specific gravity should show if these two minerals are distinct.

Tests.—Infusible. Gives a cloudy silica residue in microcosmic salt.

PSEUDOMALACHITE, $Cu_3(PO_4)_2 \cdot 3Cu(OH)_2$; LIBETHENITE, $Cu_3(PO_4)_2 . Cu(OH)_2$; OLIVENITE, the corresponding arsenate, $Cu_3(AsO_4)_2 . Cu(OH)_2$, isomorphous with liebethenite; and ERINITE, $Cu_3(AsO_4)_2 \cdot 2Cu(OH)_2$, may be quoted as examples of green copper ores which must not be mistaken for the far more common malachite.

CHALCANTHITE, $CuSO_4 . 5H_2O$, is, like azurite, one of the few triclinic minerals. Its crystals are paler blue and more translucent than those of azurite, and it is soluble in water. The water running from copper mines and containing this salt was noticed in Hungary to deposit copper in place of the iron of tools accidentally left in it; and this method of extracting copper has been regularly practised with iron bars at Rio Tinto in Spain, in Co. Wicklow, and elsewhere.

Silver.

The bead of reduced silver remains unaffected, or at the most darkens, on treatment with O.F. A large part of the world's silver is now extracted from galena.

Native Silver occurs in stringy and capillary masses in most silver mines. Sometimes shows good cubic crystals {100}, which are often grouped in linear series. H. = 2·5. G = 10·5.

A large part of the Peruvian and Ontarian ore is native silver. At Kongsberg, in Norway, masses occur up to 5 cwt. in weight. Gold is often associated.

ARGENTITE (SILVER GLANCE). Ag_2S. Ag 87·1 %.—Lead-grey to almost black. Cubic I, commonly in cubes. H. = 2·5. G. = 7·2. Sectile.

ACANTHITE is a rhombic form of Ag_2S, with forms near those of chalcosine, Cu_2S. Otherwise like argentite.

STEPHANITE. Ag_5SbS_4 ($= 5Ag_2S.Sb_2S_3$). Ag 68·36 %.—A black rhombic sulphantimonite.

Pyrargyrite. Ag_3SbS_3 ($= 3Ag_2S.Sb_2S_3$). Ag 59·8 %.—This is one of the two "red silver ores." Deep red to black; purplish red streak. Translucent to opaque. Lustre metallic-adamantine (Miers). Trigonal II. $a : c = 1 : 0{\cdot}789$. H. = 2·5. G. = 5·8.

Occurs in small dark crystals, suggesting stibnite, but easily recognised by their streak; also massive, somewhat like cinnabar.

Tests.—The antimony forms a dense white oxide on charcoal, on the surface of which a purplish sublimate of silver oxide often forms. Silver metallic bead.

PROUSTITE.[1] Ag_3AsS_3 ($= 3Ag_2S.As_2S_3$). Ag 65·45 %. The light red silver ore, being pink-red, with a scarlet-vermilion streak. Translucent in crystals, which darken on exposure to light. Trigonal, probably Class II; $a : c = 1 : 0{\cdot}804$. H. = 2·5. G. = 5·5.

Tests.—Arsenic reactions. Silver metallic bead.

POLYBASITE, $(Ag,Cu)_9(Sb,As)S_6$ ($= 9(Ag,Cu)_2S(Sb,As)_2S_3$), with Ag 73 %, is an important black ore in Mexico. Red by transmitted light.

CERARGYRITE DIVISION.[2]—This includes the "horn silver ores," so called on account of their general appearance and sectility. They resemble wax, have a resinous lustre, and are easily overlooked, until their high specific gravity (above 5) is recognised. They indicate ores of silver below them in the crust, and are sometimes streaked with native silver. As will be seen from the following grouping, the cerargyrite (or kerargyrite) minerals are silver chlorides, iodides, and bromides. The silver is about 75%.

Chlorargyrite, AgCl.—Colourless.

Embolite, Ag(Cl,Br).—Green-grey.

Bromargyrite, AgBr.—Green-grey.

Iodembolite, Ag(Cl,Br,I).—Yellow.

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[1] A complete study of the relations of proustite and pyrargyrite was made by H. A. Miers, *Min. Mag.*, **8** (1888), 87.

[2] See Prior and Spencer, *Min. Mag.*, **13** (1902), 184.

Iodyrite, AgI.—Yellow to brown.

The yellow and brown tints thus appear to be due to iodine. All these minerals are cubic, but crystals are very rare. Iodyrite is trigonal at ordinary temperatures, but cubic above 146°.

Gold.

Gold is largely found native, but is now extracted from a number of minerals, such as pyrite, and from silver, copper, and lead ores.

Native Gold usually contains silver, up to some 16 %. Gold colour, untarnished. Cubic; octahedral crystals fairly common, in groups, but often platy or massive. H. = 3. G. = 15·5—19·5, the lower values being due to silver.

Tests.—Easily fusible. Malleable. Soluble only in aqua regia (HCl and HNO_3).

Occurs very generally diffused in quartz veins, in which crystalline patches may be visible with the unaided eye. Its history is illustrated by the fact that gold is being deposited with silica in the geyser-sinter of Steamboat Springs, Nevada. The older gold-workings, as in Ireland and Peru, were in alluvium, since the very high specific gravity of gold leads to its ready concentration on the floors of river-gravels. The associated sands include minute gold particles, which can be obtained profitably even by panning with the hand. The parent veins are now being crushed in most countries, and surprisingly low percentages pay for extraction with the chemical processes employed. Numerous ores containing accessory gold help to maintain the world's supplies.

In the famous Rand district of the Transvaal Province of South Africa, nearly all the rocks, igneous or sedimentary, contain some gold; but the great source is the steeply dipping quartz-conglomerate known as "banket," from its resemblance to an almond-cake. The gold here sometimes occurs moulded on the pebbles, and filling up the interspaces. Only a small amount exists in the quartz pebbles themselves, and some authors have regarded the gold as brought in by infiltration after the accumulation of the rock. Rolled blocks of pyrite, however, occur as part of the conglomerate, and it has been urged that the gold was deposited as alluvial auriferous pyrites contemporaneously with the other pebbles, and has been set free by the decomposition of the pyrite, as so often occurs in sulphide-bearing veins.

The larger masses of gold in alluvial deposits, showing signs of rolling, are styled *gold nuggets*. When that weighing 22 oz. Troy was discovered in 1795 in Co. Wicklow,[1] it was the largest known. In 1857, a nugget was obtained at the Kingovver diggings in Victoria, weighing 1743 oz., and the Welcome nugget from Baker Hill, Ballarat, found in 1858, weighed 2166 oz., 2020 of which represented gold.

ELECTRUM is gold naturally alloyed with some 20 to 30% of silver.

CALAVERITE, $AuTe_2$, yellowish metallic, G. = 9, and SYLVANITE (GRAPHIC TELLURIUM), $AgAuTe_4$, metallic white or grey, G. = 8, illustrate the frequent association of gold with tellurium.

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[1] The Wicklow nuggets are carefully described by V. Ball, *Sci. Proc. R. Dublin Soc.*, **8** (1895), 311, and are of interest in view of the considerable use of gold in prehistoric times in Ireland.

CHAPTER XV

THE SILICATES. ALUMINIUM SILICATES AND THE FELSPARS

Introductory.

About half the earth's crust by weight is composed of silica, while another quarter consists of alumina, and hence it is natural that silicates, and especially aluminium silicates, should have a high geological importance. The common chlorides, carbonates, and sulphates have, moreover, been largely derived from silicates during processes of denudation. Almost all the sodium in the sea, and the calcium in massive limestones, may be traced back to silicate rocks, and from time to time fresh masses of these rocks reach the surface in a molten state and give us some suggestion of the composition of the primitive crust. Few such rocks, however, can now be regarded as the product of virgin magmas, since so much remelting and intermingling has gone on during long geological ages in the lower regions of the crust. The fact that the oldest rocks known to us are of sedimentary origin shows how the silicate masses which now invade them may result from a reconstitution of materials that have already been at the surface under other forms. These hot igneous invaders tend to reproduce anhydrous silicates in place of the hydrous silicates of the rocks into which they are intruded, and one of the commonest features of what is known as contact-metamorphism is the transference of siliceous matter from an intrusive mass into its surroundings. Wollastonite and calcium garnet are thus built up in limestones, and conspicuous or microscopic veins of molten rock, crystallising ultimately as quartz and felspar, penetrate along the parting-planes of schists and shales. The silica that is lost in solution during the formation of the bulk of sediments out of older silicate rocks becomes restored to some extent during metamorphic processes. At the same time, silicates arise from a rearrangement of the material of sediments under the stimulus of igneous invasion or of earth-pressures; a dull argillaceous mass may become transformed into a gleaming mica-schist, while an earthy and decomposed "greenstone" may develop blades of amphibole far more handsome than anything that it contained among the products of its original consolidation. While, then, some mineral silicates are typically of igneous origin and others as typically metamorphic, a large number arise under very various conditions. Temperature is one of the most important factors that has determined the characters on which we rely for their classification as mineral species.

Most mineral silicates can be expressed as salts of the known silicic acids, though some ingenuity may be required in constructing a constitutional formula for complex series. Disilicic acid, $H_2Si_2O_5$, thus forms *disilicates*, such as petalite, $LiAl(Si_2O_5)_2$, where the monovalent Li and the trivalent Al together replace four atoms of hydrogen. Orthoclase, $KAlSi_3O_8$, is a *polysilicate* or *trisilicate*, the corresponding polysilicic or trisilicic acid being $H_4Si_3O_8$. The *metasilicates*, based on metasilicic acid, H_2SiO_3, form a very important group, of which enstatite, $MgSiO_3$, may be mentioned as a type. Talc, $H_2Mg_3(SiO_3)_4$, is also a metasilicate. Orthosilicic acid, H_4SiO_4, gives us the equally important *orthosilicates*, such as olivine, $(Mg,Fe)_2SiO_4$, anorthite, $CaAl_2(SiO_4)_2$, and grossularite, the calcium garnet, $Ca_3Al_2(SiO_4)_3$.

All silicates leave an undissolved residue, which is said to be tridymite, in a bead of microcosmic salt, even after prolonged heating; but the slow solution of mineral fragments of some other substances, such as titanium dioxide, makes this test somewhat unsatisfactory. Few mineral silicates are completely decomposed by boiling in hydrochloric acid, and a fusion-mixture must ordinarily be employed before the silica can be separated. Among the silicates that are soluble in acid, some yield a gelatinous residue of metasilicic acid (p. 158).

Aluminium Silicates.

The simple aluminium silicate, Al_2SiO_5, which may be expressed either as a metasilicate, $(AlO)_2SiO_3$, or an ortho-silicate $Al(AlO)SiO_4$, does not form common mineral species, in comparison with the hydrous form $H_4Al_2Si_2O_9$. The latter, resulting from the hydration of other aluminous silicates, is an important constituent of clays and shales.

Kaolin (Kaolinite). $H_4Al_2Si_2O_9$ = perhaps $H_4Al(AlO)(SiO_4)_2$. SiO_2 46·5, Al_2O_3 39·5, H_2O 14·0%.—Colourless, but usually as a white powder, consisting of very minute transparent plates with irregular edges. Monoclinic; minute six-sided plates. Perfect basal cleavage. H.=2·5. G.=2·62.

The name is of Chinese origin, signifying "high ridge," the place where the famous porcelain-clay of China is dug out. Pure kaolin earths of this kind, known as *china-clay*, are unfortunately rare, though kaolin occurs throughout the decomposing regions of most felspathic rocks. The attack of acids, and especially of the carbonic acid found in rain-water that has dissolved carbon dioxide from the air, tends to break up aluminous silicates and to remove sodium, potassium, or calcium, together with some of the silica, in solution. Alkali-felspars, and possibly alkali-micas, in this way pass into a "kaolinised" condition, water combining with the alumina and the residual silica. The white powdery kaolin spreads through them, and they sometimes crumble between the fingers; but, where the process goes on upon a surface exposed to wind and rain, the kaolin is readily removed, and is unlikely to become thoroughly sifted out by natural action from the fine fragments of quartz and mica and undecomposed felspar that are commonly associated with it at its place of origin. The common muds or clays result from continued washing of such materials; but they usually contain at least 60% of silica, the excess over the 46·5% required by kaolin being in the form of finely comminuted quartz. Where, however, subterranean decay has gone on throughout a mass rich in alkali-felspars, kaolin, preserved from scattering action, may accumulate as a valuable product. Granite may thus be locally attacked by water containing carbon dioxide or by the stronger hydrofluoric acid escaping from the earth.[1] In such rock-masses, which were once permeated by gases and liquids, decomposition may be exceptionally thorough. While all the felspars are then kaolinised, secondary quartz may arise from the silica that has been separated from them. Further changes may result in the complete disappearance of the aluminous material and the conversion of the rock into a mass of quartz and tourmaline; but in places the decomposition has been arrested at the kaolin stage. Artificial washing of the crumbling rock is sufficient to separate the china-clay from coarse ingredients, and such refined earths have been the foundation of the porcelain industries of Pekin, Meissen, and Limoges. The kaolin of St. Austell, in Cornwall, which is extracted from deep pits in altered granite, is sent to the potteries of Staffordshire, to meet there the coal necessary for its firing. It was long before the secret of the translucency of Chinese porcelain was discovered in Europe, and at Sèvres glass was mixed with the kaolin to produce the desired effect. Some of the undecomposed felspar, or even of the associated granite as a whole, when melted up with the clay, gives rise to a true china and not merely a dull white earthenware.

The question of what is true *clay* has been discussed by physicists, mineralogists, and agriculturists, and it has been sometimes urged that mere fineness of grain accounts for the plasticity and other properties of clay.[2] "Clays," however, show a remarkable shrinkage on drying, after being puddled in water, and the dry mass does not fall to pieces until again immersed in water. Searle states that the normal shrinkage is as much as 38 per cent. Kaolin particles are platy, and may thus lie at various angles with one another when slowly deposited from suspension in natural waters. The high percentage of pore-space, amounting to some 55 per cent. in plastic clays, may be thus accounted for, and it allows of considerable shrinkage. Mica particles, which abound in clays, of course produce the same effect. When the water of the moist clay evaporates down to thin films surrounding groups of particles, the members of these groups can be drawn appreciably nearer to one another by the surface-tension of the films. This fact, however, does not seem to account for the compactness of the final mass, and it has been suggested that the special properties of clay depend on the proportion in which particles are present with a diameter of less than 0·005 or even 0·002 mm. If clays with a large proportion of these particles can be shown to approximate to the composition of kaolin, a mineral basis for "true clay" may be regarded as established. At the same time, coarse kaolin-earths have poor plasticity, so that kaolin, unless in a fine state of division, cannot be regarded as synonymous with clay.[1] F. W. Clarke[2] expresses the general belief "that the plasticity of a clay is due to the colloid substances which it happens to contain."

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[1] See references and discussion by F. H. Butler, "Kaolinisation and other changes in West of England Rocks," *Min. Mag.*, **15** (1908), 136; and especially H. Stremme, *Fortschritte der Mineralogie*, **2** (1912), 87.

[2] See discussion, with references, by A. B. Searle, "The Natural History of Clay" (1912), 20.

In common clays the kaolin present is masked by ferruginous and organic impurities. White china clay, or "pipe clay," collects as an exceptional product in the floors of pools in the neighbourhood of kaolinised rocks.

When heated to 1350°, kaolin passes into sillimanite, with possibly cristobalite; but Mellor and Holdcroft[3] believe, from experiments on the solubility of the constituents, that between 500° and 1350° kaolin is separated into silica, alumina, and water, the silicate Al_2SiO_5, in the form of sillimanite, being produced by recombination at the higher temperature.

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[1] G. Hickling, who regards kaolin as a product of muscovite and of the secondary mica in felspars, denies that it is essential to ordinary clay (*Trans. Inst. Mining Engineers*, 1908).

[2] "Data of Geochemistry," *U.S. Geol. Surv.*, *Bull.* 491 (1911), 478.

[3] See H. Stremme, "Die Chemie des Kaolins," *Fortschritte der Mineralogie*, **2** (1912), 100; and Mellor and Holdcroft, *Trans. English Ceramic Soc.*, **10** (1911), 94, and *Pottery Gazette*, **36** (1911), 680, and **38** (1913), 65.

Tests.—Infusible before the blowpipe; gives a fine aluminium reaction with cobalt nitrate. Soluble in H_2SO_4, but only slightly attacked by HCl.

Opt.—Average refractive index 1·563; birefringence very low, 0·002 to 0·004.[1]

Andalusite. Al_2SiO_5.—Groth regards this as an unstable orthosilicate, $Al(AlO)SiO_4$, liable to pass over into more stable forms. Al_2O_3 63, SiO_2 37%. Grey, but often pink. Even palely coloured varieties exhibit remarkable face-pleochroism in tints of pale green when viewed down the vertical axis, and claret-red when viewed perpendicularly to this axis. Rhombic I, commonly in square prisms, the prism-angles being 90° 50′ and 89° 10′. Terminated by {001}. $a:b:c = 0·9861 : 1 : 0·7025$. $H = 7·5$. $G = 3·2$. Andalusite is a common result of contact-action of granite masses on argillaceous rocks. Mica separates out at the same time, and often obscures the mineral by becoming plastered over its surface. Its liability to alter into soft products, such as kaolin or mica, may prevent the hardness from serving as a test. The form, however, is characteristic, and crystals often measure 2 or 3 cm. across. They frequently contain abundant inclusions, which are sometimes carbonaceous, and the pink colour that seems proper to the mineral is revealed only in unclouded specimens. The impurities that have not been thrust aside during crystallisation are sometimes grouped at the angles of the prism and down its centre. Five dusky columns thus run parallel with the vertical axis, and two diagonal sheets of impurities usually connect these with one another. When the grouped impurities are prominent, the light-coloured mineral appears as a whitish cross in sections across the prism, with a dark centre and dark infillings between its bars (Fig. 101). Since these infillings contain little continuously crystallised material, they may weather away, leaving the andalusite core, which then resembles an interpenetrant cross-twin, like those of harmotome.

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[1] A. B. Dick, "Supplementary Notes on Kaolinite," *Min. Mag.*, **15** (1908), 124.

Crystals of this type are known as *Chiastolite.* Small whitish examples appear abundantly in slates affected by contact-metamorphism, as at Skiddaw in Cumberland, and Hof in Bavaria, and exceptionally bold examples occur in slates at Bimbowrie, S. Australia, and at Lancaster, Massachusetts.

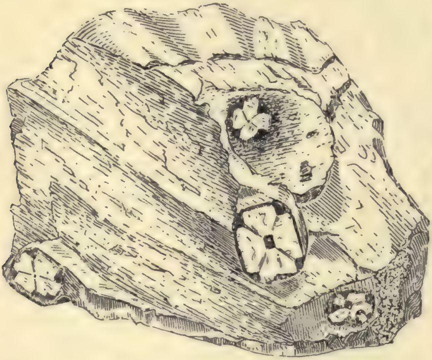

FIG. 101.—Crystals of chiastolite in altered slate, showing transverse sections. Lancaster, Massachusetts.

Tests.—Infusible. A splinter, moistened with cobalt nitrate and reheated in O.F., gives the aluminium reaction.

Opt.—Optic axial plane the brachypinacoid; α-axis parallel to *c*-axis, γ-axis to *a*-axis. $\alpha = 1{\cdot}632$, $\gamma = 1{\cdot}643$; birefringence 0·005 to 0·011. Shows marked relief in sections. Axis-pleochroism, α-axis pink, β and γ axes faint green, or colourless in thin sections. Small crystals or grains, such as occur in schists, or in granites near contact with such rocks, may appear colourless until the section is rotated in relation to the polariser, when a pink flush in two positions at once suggests this mineral.

KYANITE (CYANITE; DISTHENE). Al_2SiO_5.—Groth regards this as the stable metasilicate $(AlO)_2SiO_3$. Transparent to translucent; colourless to a characteristic pale blue. The blue tint sometimes reveals itself when a kyanite-schist is struck with the hammer in the field. Triclinic; elongated prismatic forms, with {110} and vertical pinacoids. Perfect basal cleavage. H. = 4—7 according to direction. G. = 3·6. The mineral is named from its sea-blue tint, and is well known by the exceptional examples, associated with rich brown stauroilite, in a white shimmery sodium-mica schist on the south side of the St. Gotthard Pass near Airolo. Like andalusite, it is essentially a contact-mineral, and Weinschenk has suggested, from its specific gravity, that it arises under conditions of greater pressure than andalusite.

Tests.—Gives an aluminium reaction, like andalusite. Splinters were used, owing to their infusibility, for supporting minerals in the blowpipe-flame before platinum wire became available, and are still useful, like those of sillimanite, where the assay may destroy platinum.

Opt.—Refr. indices higher than those of andalusite (1·712—1·728). Colourless and not pleochroic in thin sections.

SILLIMANITE (FIBROLITE). Al_2SiO_5.—Colourless to white or brownish. Rhombic; long thin prisms common, occurring in bundles. Prism-angles 91° 45′ and 88° 15′ (compare andalusite). $a : b : c = 0·970 : 1 :$ an undetermined value. Both andalusite and kyanite pass into sillimanite when heated to about 1350°, and the association of fibrous patches of sillimanite in schists containing one or other of these minerals suggests that a recrystallisation at some high temperature may have occurred. Clays, when heated, commonly give rise to sillimanite.[1] A softening and even a fusion of other rock-forming minerals is, however, probable under such conditions. The needles of sillimanite penetrate, or are included in, quartz and biotite in metamorphic rocks, and sometimes form a considerable proportion of the mass.

Tests.—Like kyanite.

Opt.—Refractive indices 1·66 to 1·68; birefringence consequently higher than in the other aluminium silicates.

TOPAZ. $(F,OH)_2Al_2SiO_4$; or $(Al[F,OH])_2SiO_4$, Miers.—One example on analysis gives $Al_{12}Si_6O_{25}F_{10}$, which may be written $6Al_2O_3.Si_6(O_7F_{10})$; here the F_{10} may be regarded as replacing O_5, and the last half of the formula is equivalent to $6SiO_2$. The mineral is then seen as a member of the Al_2SiO_5 series in which fluorine replaces some of the oxygen.—Colourless to greenish, but often warm yellow-brown;

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[1] J. W. Mellor, *Trans. English Ceramic Society*. See under Kaolin.

transparent. Rhombic II, crystals being terminated at one end of the *c*-axis by pyramid-planes and domes, and at the other by a basal plane (Fig. 102). General form prismatic; angle over (110) ($1\bar{1}0$) 124° 17′; a second prism {120} is usually present, with angles 93° 11′ and 86° 49′, being thus nearly rectangular. This square prism is, in fact, a characteristic and predominant form (Fig. 14). Cleavage basal and perfect, the mineral being thus easily distinguished from quartz. H. = 8. G. = 3·5.

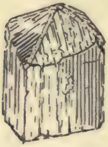
FIG. 102.—Topaz, Brazil.

Topaz occurs in cavities of granite, and is sometimes abundant where aluminous rocks, such as granite, have been attacked by hydrofluoric acid in the earth's crust. The rock known as greisen, associated with ramifying tin-bearing veins, consists of white mica, quartz and topaz. The hardness of topaz qualifies it as a gem, but its refractive index is not so high as that of corundum.

Tests.—Note the cleavage, hardness, and specific gravity, which are all useful when the mineral occurs as alluvial pebbles. Infusible. Gives a good aluminium reaction when a splinter is dipped in cobalt nitrate and strongly heated in O.F. Fused in the closed tube with the powder of previously fused microcosmic salt, gives off silicon fluoride, which deposits white silicic acid on a moistened glass rod thrust into the tube.

Opt.—Colourless in thin sections. Refr. index 1·61 to 1·62, distinctly higher than that of quartz, and of the Canada balsam in mounted sections; shows therefore good relief. Birefringence in most sections near 0·01, and thus higher than in most sections of quartz associated with it. Cleavage not usually noticeable in sections.

Petalite Division.

PETALITE. $LiAl(Si_2O_5)_2$.—A polysilicate, used for the extraction of lithium, most of which, however, comes from the lithium micas. Colourless to white. Monoclinic, occurring often in cleaved masses with curved surfaces. H. = 6—6·5.

G. = 2·4, which is an important character in distinguishing petalite from felspar.

Tests.—Note specific gravity. Fuses on edges of splinters, giving lithium flame.

The Felspars.

The Felspars, more correctly spelt Feldspars, are the most important group of rock-forming silicates. They are all silicates of aluminium with either potassium, sodium, or calcium (rarely barium), or with all three of these elements. The fundamental molecules are believed to be the polysilicates or trisilicates, $KAlSi_3O_8$ and $NaAlSi_3O_8$, and the orthosilicate $CaAl_2(SiO_4)_2$. The first of these corresponds with the composition of an ideal orthoclase, and is written, for shortness, Or; the second is that of ideal albite, or Ab; the third is that of ideal anorthite, or An. Tschermak pointed out that the commonly occurring species of felspar can be regarded as mixtures of these molecules, as is represented in the table on p. 271.

The fact that all the species but orthoclase (and the rare barbierite and hyalophane) are triclinic has led some authors to place orthoclase also as doubtfully on the margin of this system. The felspar series, however, merely illustrates the artificial character of a classification of minerals by their crystalline systems. The common characters of felspar crystals may be briefly stated:—

Crystalline Form.—Usually a combination of four planes of the unit prism $\{110\}$, the right and left pinacoid pair $\{010\}$, basal pinacoid pair $\{001\}$, and a hemidome $\{\bar{1}01\}$ or $\{\bar{2}01\}$ (Fig. 103). The angle between (001) and (010) does not deviate in any species more than 4° 10′ from a right angle, and is 90° in orthoclase. Forms occur elongated along the *a*-axis, and these are often so proportioned as to resemble square prisms, until set in their proper crystallographic positions (Fig. 104). Felspar crystals

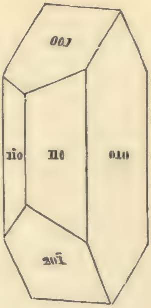

FIG. 103.

are often tabular through reduction along the *b*-axis. These board-like forms yield narrow "lath-like" sections when cut across, and a fluidal movement in the viscid igneous rock in which they arise may cause them to be arranged with their broad surfaces parallel with one another. Hence on a rock-face or in a rock-slice parallel to these surfaces the crystals appear as plates, while on any surface perpendicular to this one elongated sections alone are seen. The common Carlsbad and albite twinning (see below) reveals itself in the latter sections.

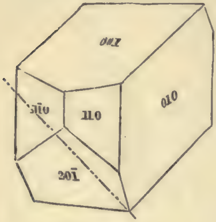

FIG. 104.

Bipyramid and *a*-dome planes are also common. In the monoclinic species orthoclase, the four planes of the clinodome $\{021\}$ appear, and the four planes of the hemibipyramid $\{\bar{1}11\}$; the triclinic character of other species of felspar is often revealed by the presence of only two bipyramid planes, one above and one below at the back parallel with it, or only two planes of the dome parallel with the *a*-axis, as, for instance, a right-hand top and a left-hand bottom plane.

Twinning.—This is a very characteristic feature. In the triclinic forms it is common about a twin-axis perpendicular to the brachypinacoid plane (010), this plane being the composition-plane (*albite type*) (Fig. 105). Also with the macrodiagonal, the *b*-axis, as the twin-axis and the plane known as the "rhombic section"[1] as the composition-plane (*pericline type*). On the brachypinacoid, the trace of the rhombic section is parallel to that of the basal plane in ANDESINE, and more highly inclined to the vertical edge (110) (010), or, to put it

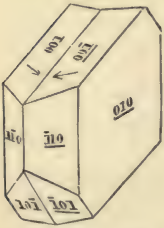

FIG. 105.—Albite twin.

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[1] See W. J. Lewis, "Crystallography" (1899), 549. The rhombic section of a triclinic prism cuts the four prism-planes in equal traces, and is thus a rhombus. It is clear that its inclination must vary with the angle (110) $(1\bar{1}0)$. Since the slope of (001) also varies in different species, the trace of the rhombic section makes various angles on (010) with the edge (010) (001).

another way, to the edge (100) (010), in varieties richer in sodium, until it is practically perpendicular to this edge in **albite**. In species richer in calcium, it is inclined at a less angle to this edge, deviating 18° from the trace of the basal plane on (010) in **anorthite**. In **microcline** it is nearly perpendicular to the trace of the basal plane. It will be seen that the twin-axes of both the albite and pericline types of twinning are nearly identical, owing to the fact that the *b*-axis in all the species is approximately perpendicular to (010). Both types are commonly repeated and even delicately lamellar, producing twin-banding on broken surfaces of the crystals (Fig. 106). The edges of the lamellæ of the albite type are seen on the planes from the zone (100) (001), while those of the pericline type appear on these planes, and also on the brachypinacoid, where they have the inclinations above noted to the trace of the basal cleavage. The lamellæ of these two types of twinning may be understood from some such illustration as the following. Take a number of rectangular cards, white on one side and black on the other. Cut a notch in one end of each. Stand the series as a pack upright, the white side of one against the black side of the next and the notches all at the top. Now turn the alternate cards through 180°, so that their notches come to the bottom. This arrangement illustrates the albite type of lamellar twinning. The same pack, in its original arrangement, may now be held approximately horizontally, to represent parallelism with the

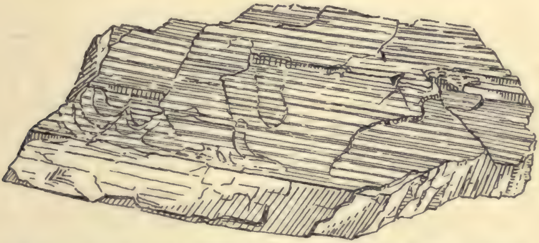

FIG. 106.—Repeatedly twinned oligoclase, cleaved parallel to the base. Tvedestrand, Norway.

rhombic section. Turn the alternate cards over, so that throughout the pack two black sides and two white sides come together, while the notches appear at the ends only in alternate cards. This illustrates the pericline lamellæ. In the actual crystals, however, the axis of apparent rotation (twin-axis) does not lie exactly in the plane of composition.

The two types of twinning may occur in the same crystal, the lamellæ in one part lying nearly at right angles to those in an adjacent or overlapping part, and producing a cross-hatched effect on planes or in sections from the zone (100) (001). In monoclinic crystals the albite type of twinning is impossible, since (010) is a plane of symmetry, and the half of the crystal on one side of it is thus already a reflection of that on the other side. If two monoclinic forms, however, are set with their *c* and *b* axes parallel, and the edge (110) ($1\bar{1}0$) of one coincident with the same edge of the other, they will form a reflection-twin across the orthopinacoid ($\bar{1}00$). They can now be applied to one another by their clinopinacoids (010), and a typical form, known as the *Carlsbad twin*, results. The joint form is usually interpenetrant, as is shown in Fig. 111. The two parts can be brought into crystallographic coincidence by a rotation of one of them through 180° about a line perpendicular to (100) or about the *c*-axis. The Carlsbad twin is most conveniently described as having the *c*-axis as the twin-axis and the clinopinacoid-plane as the composition-plane; but the orthopinacoid-plane (100) is often given as the twin-plane, since that perpendicular to the *c*-axis is not a plane of the crystal.

Carlsbad twinning occurs also in triclinic felspars, lamellar twinning of the albite type being combined with it within the two portions of the Carlsbad form.

Felspars elongated along the *a*-axis, as shown in Fig. 104, are sometimes twinned about a clinodome, which is so sloped as to cut diagonally across the rectangular or almost rectangular ends of the crystal. From their occurrence in orthoclase at Baveno on the Lago Maggiore, these are styled *Baveno twins*. They are found fairly often in other parts of the world, as in the granite of the Mourne Mountains. The grouping of the two parts of the twin brings to one end of the elongated crystal four rather kite-shaped planes, which are parts of two *b*-dome planes and two prism planes (Figs. 104 and 107). In the untwinned form one of these dome-planes and one of these prism-planes would be found at the opposite end of the elongated crystal, where, indeed, the remainder of each may be looked for in the twin.

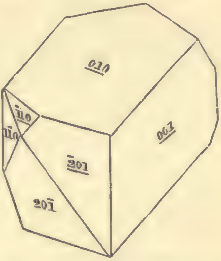

FIG. 107.—Baveno twin.

The *Manebach twin* in felspars has its twin-axis perpendicular to the basal plane (Figs. 108 and 109), which is also the composition-plane.

Cleavage.—Two good cleavages parallel to (001) and (010). Crystalline fragments thus furnish the fundamental angles required for specific determination.

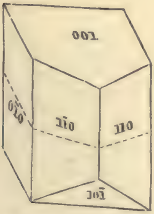

FIG. 108.—Untwinned felspar of the type found in the Manebach twin.

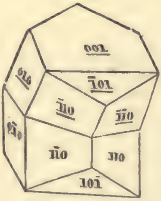

FIG. 109.—Manebach twin.

Hardness.—In all species = 6.

Specific Gravity.—Fairly low, varying from 2·56 in orthoclase to 2·76 in anorthite.

Colour.—Typically light. Colourless and transparent to grey, white, yellowish, pink-red, and rarely green, in the common opaque varieties. The opacity is due to inclusions, which are usually products of decomposition.

Schillerisation is common, producing a grey-blue shimmer in some soda-orthoclase, a spangled "aventurine" effect in the variety of oligoclase styled "sunstone," and a brilliant play of colours in certain grey specimens of labradorite. "Moonstone," with its delicate sheen, is schillerised orthoclase or albite. The plates that cause the play of colours in felspar are sometimes developed along three sets of planes within the crystal (Fig. 1).

The minerals of the felspar series are best appreciated when arranged with their specific characters in a tabular form. Owing to the slope of the basal plane to the brachypinacoid in triclinic forms, and the consequent inclination of the cleavages, the triclinic species have been collectively styled *plagioclases*, or "obliquely cleaving" felspars, in opposition to orthoclase, in which the cleavages are at right angles. The table, however, will at once show that this division is highly arbitrary, and it tends to obscure the close crystallographic and physical relationship between orthoclase, microcline, and albite. The grouping into orthoclastic and plagioclastic felspars finds, however, some justification in the fact that orthoclase does not exhibit repeated twinning, while this feature is common in all plagioclases. Hence, on fractured surfaces of rocks, where the felspars are broken through in various directions, the typical Carlsbad twinning of orthoclase is revealed in sections that are oblique to (010). The basal cleavage in the two parts slopes in different directions, and one part reflects the light from glancing cleavage-surfaces, while the other appears dull. Similarly, the plagioclases show in such sections on the face of the rock-specimen a number of delicate bands, miscalled striæ, the alternate ones reflecting the light and the others remaining dull (Fig. 106). The pocket-lens may be required for their observation; but the repeated twinning is of course a striking feature in rock-slices when crossed nicols are employed. Before further determinative tests can be applied, it may be convenient to note in this way that a plagioclase, and not orthoclase, is present in a rock.

Table of the Felspars.

Species.	Chemical composition.	SiO_2 %	Specific gravity.	Refractive indices. (Wülfing, 1905).	Angle between cleavages (010) (001).
Orthoclase . .	$KAlSi_3O_8$	64·7	2·56	1·519 1·523 1·525	90°
Soda-orthoclase	$(K,Na)AlSi_3O_8$	66·0	2·57–2·60	1·523 1·528 1·529	90°
Microcline . .	$KAlSi_3O_8$	64·7	2·56	1·519 1·523 1·529	89° 30′
Soda-microcline	$(Na,K)AlSi_3O_8$	66·0	2·57–2·60	1·523 1·528 1·529	89° 30′
Albite . . .	$NaAlSi_3O_8 = Ab$	68·8	2·61–2·63	1·529 1·532 1·539	86° 24
Oligoclase . .	Ab_6An_1—Ab_3An_1	65–62	2·63–2·65	1·540 1·544 1·547	86° 20′
Andesine . .	Ab_3An_1—Ab_1An_1	62–56	2·65–2·68	1·549 1·553 1·555	86° 14′
Labradorite .	Ab_1An_1—Ab_1An_3	56–49	2·68–2·72	1·555 1·558 1·563	86° 12′
Bytownite . .	Ab_1An_3—Ab_1An_6	49–47	2·72–2·74	1·563 1·564 1·569	
Anorthite . .	$CaAl_2(SiO_4)_2 = An$	43·3	2·76	1·575 1·584 1·588	85° 50′

The alkali-felspars produce kaolin on attack by water charged with carbon dioxide (see under Kaolin), though albite sometimes resists longer than orthoclase.[1] Orthoclase, in contradistinction to albite,[2] very frequently develops minute plates and wisps of muscovite throughout its crystals, which are detected in thin sections by their platy cleavage and high interference-colours in polarised light. The felspars rich in calcium, on the other hand, occasionally leave pseudomorphs in calcite, but far more often pass into a white or grey granular toughened condition through the development of calcium silicates, such as zoisite, epidote, grossularite, etc. The product was formerly described in gabbros under the name of *saussurite*, and the result is still said to be "saussuritic" (see under Zoisite).

Tests.—Special features of interest in the several species will be noted later; but the above table suggests the importance of specific gravity determinations. Here the diffusion-column (p. 19) proves of special service, and small fragments may be selected under the microscope, free from inclusions or decomposition-products, and dropped into a column, the density of which ranges from 2·45 to 2·9. **Anorthite** is practically infusible before the blowpipe; but the other species show a slight rounding on the edges of thin splinters, which is quite characteristic in the alkali felspars. Day and Allen[3] have determined the fusibility of certain types as follows:—

Ab_3An_1, 1340°; Ab_1An_1, 1419°; Ab_1An_5, 1500°; Anorthite (An), 1532°.

A. Brun[4] gives the following: **Orthoclase** 1300°; **Soda-orthoclase** 1250°; **Albite** 1250°; **Labradorite** 1370°; **Anorthite** about 1500°.

J. Szabó introduced in 1876[5] one of the most practical methods of determining small grains of felspar, such as are procurable even from fine-grained rocks. He selected a standard Bunsen gas-burner 1 cm. in diameter, giving a flame 14 cm. high, and capable, for work at a higher temperature, of being fitted with an iron cone resting on a three-rayed support. This cone is 3 cm. in its upper diameter and rises 3 cm. above the orifice of the burner.

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[1] McLintock and Hall, *Min. Mag.*, **16** (1912), 300, on "Granite in Lundy Island."

[2] J. S. Flett, *Mem. Geol. Survey* on St. Austell (1909), 117.

[3] "Isomorphism and Thermal Properties of the Felspars," *Carnegie Institution*, *Pub.* 31 (1905), and *Nature*, **72** (1905), 259.

[4] "Recherches sur l'exhalaision volcanique" (1911), 31.

[5] "Ueber eine neue Methode die Feldspathe auch in Gesteinen zu bestimmen." Franklin-Verein, Budapest.

The particle of felspar used is such as would fuse to a globule close on 1·5 mm. in diameter. It should be selected as a pure sample with a lens or a microscope. A specimen may be allowed to decrepitate along its cleavage-planes in a heated glass tube, and the particle can be chosen from material that has thus been previously broken up. It is not then likely to fly when introduced into the flame.

A loop is then made in a moderately thin platinum wire, which can be held at a given height in the flame on any convenient support. A knitting-needle stuck vertically through the cork of a steady and short bottle, with another cork sliding up and down on it, will serve well. The wire can be held in a slit cut in the sliding cork. A plate of wood 5 mm. thick should be at hand to slip under the bottle when required. This simple type of apparatus has suggested itself in frequent practice.[1]

The cork holding the wire is taken in the hand and the loop is dipped into distilled water. The loop is then made to touch the selected particle so that it can be brought up resting on the upper surface of the loop. Approach the loop very carefully to the Bunsen flame, so as to dry off the water. Even if the particle falls off more than once before it finally sticks to the loop, it must be remembered that the method, as a process of fairly quantitative analysis, is a very quick one. When the particle sticks, slip the cork on to the knitting needle and adjust so that the loop comes just to the top of the Bunsen burner. Slip the wooden plate 5 mm. thick under the supporting bottle; the particle now lies exactly 5 mm. above the base of the flame. Bring it into the margin of the flame, and observe against a dark screen any colouration imparted during one minute.

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[1] G. Cole, "Simple Apparatus for Flame-reactions," *Geol. Mag.* (1888), 314.

Sodium displays itself as a yellow column up the side of the flame, five degrees being recognised (Fig. 110, I). A thick

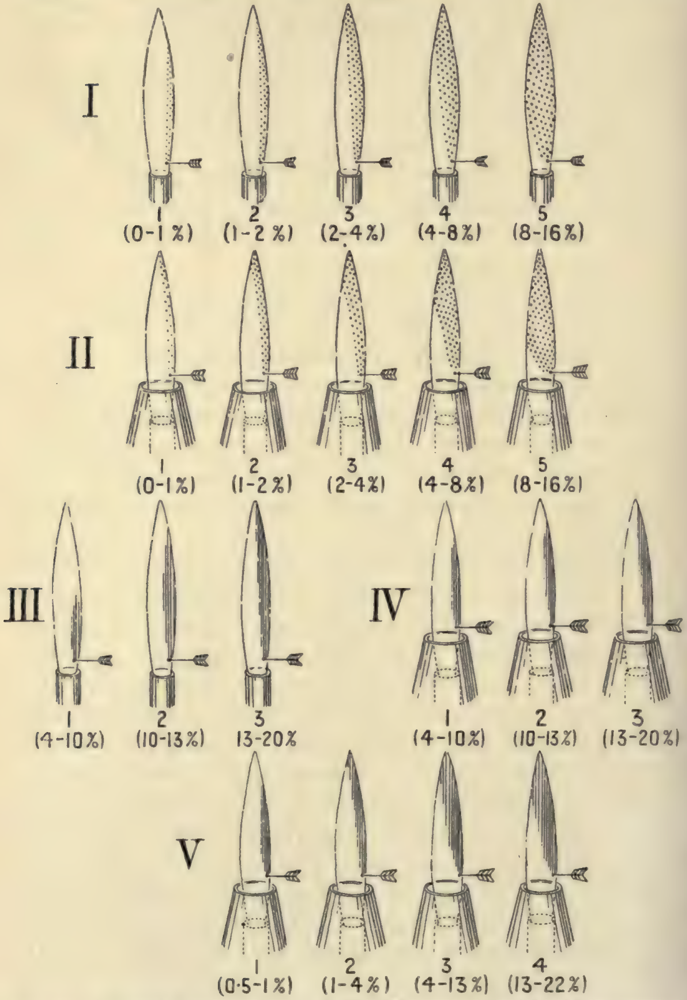

FIG. 110.—Szabó's flame-reactions. Sodium flames are dotted, while potassium flames are marked with vertical lines. (This diagram can be set up side by side with the Bunsen burner when the experiments are being made.)

piece of blue glass is used, during the same minute, to estimate potassium, three degrees being recognised (III). The iron cone is then put on, and the same particle is adjusted as before, with the aid of the wooden plate, so as to lie in the flame 5 mm. above the top of the cone. Five grades can again be observed in the sodium flames (II), and three in those due to potassium (IV). The addition of powdered gypsum, by converting the alkali-silicates into sulphates, intensifies the potassium flame produced (V). Calcium may usually be inferred in a felspar from a low degree of alkalies.

Following Szabó's degrees, as shown in the diagram of the coloured flames (Fig. 110), we have:—

Mineral.	Without cone.		With cone.		With gypsum.
	Na	K	Na	K	K
LEUCITE . . .	2–3	3	2–3	3	4
Orthoclase . . .	1–3	2–3	1–3	2–3	3–4
Soda-orthoclase .	3–4	1	3–4	1–2	2–3
Albite	5	0	5	0	0
Oligoclase . . .	3–5	0	4–5	0	1–2
Labradorite . .	2–3	0	2–3	0	1–2
Anorthite . . .	1–2	0	1–2	0	0–1

Potassium can, however, be far better estimated by the method of fusion in a sodium carbonate bead, described on p. 160. Three grades may be established, and the observer will do well to note these for his own eye when working with determined and typical specimens. Grade 1, when a definite potassium band is seen in the lower part of that side of the flame on which the mineral particle lies, represents some 3–4 % of potash; but smaller amounts may of course be recognised, as in the oligoclase of Ytterby, which contains less than 1 %. Grade 2 may be made to correspond with 8 %, and grade 3 with 12 % and upwards. In grade 3 the colouration seems to occupy a large part of the Bunsen flame, and all true microclines and orthoclases rise to this grade. **Soda-orthoclase** comes under grade 2, and **soda-microcline** a little below it.

Opt.—From the *refractive indices* given in the table above for typical species, it will be seen that the relief of felspars in rock-slices is low even in species rich in calcium. The Becke test is here very useful in discriminating between felspars that lie on either side of **oligoclase**, which has refractive indices almost exactly equal to that of ordinary Canada balsam.

The *birefringence* rises from 0·006 (weaker than that of quartz) in **orthoclase** to over 0·010 in **anorthite** (a little stronger than that of quartz). Low grey and whitish tints are consequently alone seen in thin rock-slices, in contrast with the higher colours of associated monoclinic pyroxenes, amphiboles, or olivines.

The *extinction-angles* in felspars may be studied on cleavage-flakes parallel to (010) or to (001), the guide-line being in each case the trace of the other cleavage, which cuts across the flake. In each case this is parallel to the edge (001)(010), which is indicated on basal flakes by the trace of the albite type of lamellæ. On (001) **albite** and **labradorite** show small extinction-angles, 5° and 9° respectively, on opposite sides of the guide-line, while **anorthite** gives the high angle of 37°. **Oligoclase** gives practically straight extinction (1° to 3°). On (010), if the plate is so laid that the trace of the basal cleavage is upright in the field of the microscope, and the obtuse angles formed by it and the direction of the *c*-axis are below on the left and above on the right, **albite** and **labradorite** are extinguished at almost equal angles (20° and 24°) on rotation to the left for albite and to the right for labradorite. **Anorthite** requires a rotation of 37° to the right; **oligoclase** again shows small angles (5° to 10° to the left). Where a cleavage-flake is of unknown orientation, **oligoclase** gives in any case small angles of extinction from the trace of the second cleavage, while ANDESINE gives nearly straight extinction. **Anorthite** for both flakes gives an angle approaching 40°. In **orthoclase**, however, extinction is straight on (001), and from 5° to 10° to the left on (010), which fails to distinguish its flakes from those of oligoclase.

In thin sections the trace of the albite type of lamellæ provides an excellent guide-line. Michel Levy[1] pointed out that sections of triclinic felspars cut parallel to the twin-axis of the albite lamellæ show extinctions for the alternate lamellæ that are symmetrical on either side of this guide-line. Such sections are recognisable in rock-slices by showing equal illumination for the two sets of lamellæ when the traces of their composition-planes are set upright or horizontal between crossed nicols in the field. The difference of shade in the lamellæ then disappears. The trace of their junctions or the brachypinacoidal cleavage serves as the guide-line. When rotated to the right, extinction occurs for one series of lamellæ; when to the left, the alternate series becomes extinguished, *after the same angle of rotation.* These symmetrical extinction-angles are by no means the same for all sections from the zone which furnishes them, that is, the zone perpendicular to the brachypinacoid. In one section, which in all species makes a small angle with (001), the extinction-angle is zero, and sections should be selected in a rock-slice which show symmetrical extinctions at the highest obtainable angle. Though this may not be the maximum angle for the particular species, its measurement will usually eliminate certain species and set the observer on the right track. If six or seven examples show small angles, we may fairly exclude the felspars rich in calcium. If we obtain one example of symmetrical extinction with an angle as high as 25°, our felspar is clearly towards the calcium end of the series.

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[1] "Détermination des Feldspaths" (1894), 31. See also diagram in Iddings, "Rock Minerals" (1911), 226, and F. E. Wright, *Amer. Journ. Sci.*, **17** (1904), 387.

The maximum angles ascertained by Michel Lévy are as follows:—

Microcline, 18°
Albite, 16°
Oligoclase, 5°
ANDESINE, 16°
BASIC ANDESINE, 22°
Labradorite, 27°
Basic Labradorite, 38°
BYTOWNITE, 45°
Anorthite, 53°

The cases of doubt are evidently when microcline, albite, or andesine is present. Microcline is usually distinguished by its microscopic cross-twinning (see p. 280). Similarly orientated lamellæ of albite and andesine exhibit their maximum extinction-angles when rotated in opposite directions from the guide-line; but this point cannot be appreciated in the haphazard sections in rock-slices, where we know nothing of the orientation of a particular set of lamellæ. The bright-band (Becke) test for refractive index decides, however, between them, since **albite** has indices lower than that of the balsam and ANDESINE has distinctly higher indices. Sections can almost always be found on the margin of the slice, on which the test can be applied.

The albite twinning is often combined in triclinic felspars with the Carlsbad type, and usually one-half of the Carlsbad twin displays more albite lamellæ than the other. Lévy utilised the fact that a section perpendicular to (010) does not traverse the two parts of the triclinic Carlsbad twin in the same optical position; hence symmetrical extinction cannot occur at the same angle in the lamellæ of both parts. While in species rich in calcium the angle is large in one part, it may be near zero in the other. In **oligoclase** and **albite** the symmetrical extinctions occur in the two parts at closely similar angles for all sections from the zone perpendicular to (010).

The *optic axial plane* in **orthoclase** is usually perpendicular to (010), but sometimes is parallel to that plane. In **albite** and **oligoclase** it is nearly perpendicular to the *c*-axis, and the emergence of both optic axes can be seen in thick cleavage-plates parallel to (010).

A few notes may now be made as to the appearance and mode of occurrence of important species.

Orthoclase. SiO_2 64·68, Al_2O_3 18·43, K_2O 16·89%; but Na_2O always present.—The prism-angle $(110)(1\bar{1}0)$ is 118° 47′. Carlsbad twinning is very common in rock-forming crystals (Fig. 111), though sometimes the diagonal position of the composition-plane in a square section points to a Baveno twin. The ready reflection of light in broken specimens from only one-half of the twin calls attention to the different slope of the basal cleavage in the two halves, and hence to the simple character of the twinning. This feature is often noticeable upon a sunny day on surfaces of granite in the field. A pink-red colour is more common in orthoclase and microcline than in other felspars, and is due to the presence of red schiller-plates throughout the crystals. A good deal of felspar in granite has been styled orthoclase that is in reality microcline.

Sanidine, named from σάνις, a table, is a transparent variety, often misleadingly styled "glassy," occurring in lavas rich in silica and potash. Its crystals are commonly platy through shortening of the *b*-axis. In composition it often approaches soda-orthoclase.

Adularia is a transparent variety occurring in some veins, as in the St. Gotthard region, in fine crystals, consisting of {110}, {$\bar{1}$01}, and {001}, the absence of the pinacoid {010} giving a sharp-edged effect at the ends of the *b*-axis.

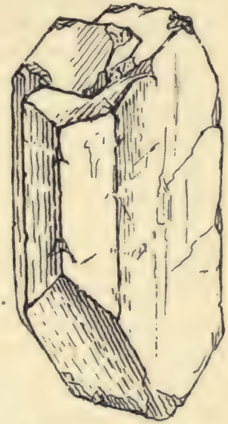
FIG. 111.—Orthoclase, Carlsbad, Bohemia.

Tests.—The flame-reaction in a sodium carbonate bead is the most satisfactory test, but does not distinguish orthoclase from microcline (see p. 275).

Opt.—The simple twinning is a very useful character in rock-slices. With the clinopinacoidal cleavage as the guide-line, the extinction is straight on the basal cleavage-flakes, and for both parts of the Carlsbad twin in all sections from the zone perpendicular to (010).

Soda-Orthoclase.—Varieties approaching soda-microcline remain monoclinic, according to Iddings,[1] so long as the soda does not equal the potash molecularly. The percentage which gives this equality is K_2O 8·45, Na_2O 5·57.

HYALOPHANE contains molecules of orthoclase and celsian (Cel), from Or_4Cel_1 to Or_7Cel_3. Monoclinic. G. = 2·7—2·8, being raised by the barium. (See Celsian below.)

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[1] "Rock Minerals" (1911), 235.

Microcline.—Closely resembles orthoclase, but shows minutely lamellar twinning of both the albite and pericline types, the edges of the lamellæ being practically perpendicular to one another on planes of the zone (100)(001). These produce a cross-hatched effect, visible on the surfaces of crystals with the naked eye. Microcline is common in granite, and especially in the eutectic intergrowths with quartz known as graphic granite. It is white, yellowish, or pink, like orthoclase. The green crystals (*amazon stone*) from Pike's Peak, Colorado, are well known.

Opt.—The double twinning is conspicuous in sections other than those parallel to (010). The maximum symmetrical extinction-angle for the albite type of lamellæ in the zone perpendicular to (010) is 18°, being 15° 30′ on basal cleavage-flakes. If extinction is obtained in one set of lamellæ from the albite series, one of the sets of the pericline lamellæ becomes extinguished at the same time, the black bands perpendicular to one another being a characteristic feature. Optic axial plane perpendicular to (010) and inclined about 5° from the basal plane.

SODA-MICROCLINE. Na_2O about 6% and upwards.—Shows the minutely lamellar double twinning of microcline; but the structure is at times so delicate as only to be visible in thin slices under the microscope. Crystals giving rhomboid and sometimes almost elliptical cross-sections occur in the so-called "rhomb-porphyries" of southern Norway. *Anorthoclase* is a variety with some lime, from Pantelleria, off Tunisia.

Opt.—The extinction-angle of the albite lamellæ on basal cleavage-flakes becomes much reduced in comparison with that in microcline, and is sometimes almost straight.

Albite. SiO_2 68·62, Al_2O_3 19·56, Na_2O 11·82 %. To a geologist, the chief interest of albite is not its occurrence in certain veins as white well-developed crystals, but its frequent appearance as a secondary product in igneous rocks. "Albitisation" takes place among the felspars of basic rocks, such as dolerites and basalts,[1] just as "uralitisation" may set in among the pyroxenes. Granular crystals commonly arise, and sometimes replace all the older felspathic ingredients of the rock. The mass appears to become richer in sodium during the change, and H. Dewey and J. S. Flett[1] have suggested that this sodium has been in some cases imported by vapours during the cooling of lavas from a molten state. Albitisation is common in a series of greenish igneous rocks known as the "spilitic series," and the material of some felspathic veins, obviously of secondary origin, is sometimes albite.

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[1] See, for instance, Bailey and Grabham on rocks of Arthur's Seat, Edinburgh, *Geol. Mag.* (1909), 250.

Pericline is a variety from the Alps in rather tabular crystals, with a shortened *c*-axis, and twinned with the *b*-axis as the twin-axis (pericline twinning). See p. 266.

Perthite, the original examples being from Perth, in Ontario, is an intergrowth of albite and orthoclase. The bands of repeatedly twinned albite appear irregularly bounded in thin sections, though with a general tendency to parallelism; but the lamellæ of the albite type within them are parallel with the clinopinacoid of the orthoclase, showing the isomorphous character of the intergrowth.

BARBIERITE.[2]—Composition like albite, but monoclinic. Refractive indices lower than those of albite. The type is from Kragerö, in Norway, and contains 1·15% of K_2O. W. T. Schaller, who names it, believes that this mineral explains the isomorphous "albite" molecules in orthoclase.

Oligoclase. SiO_2 about 63%.—K_2O usually present (see Flame-tests, p. 275). A very common felspar in the diorite-andesite series, and in granite, where it includes almost all the lime present in the rock.

Opt.—The small extinction-angles on both cleavage-plates (p. 276) should be borne in mind.

ANDESINE.—*Opt.*—The extinction-angles on cleavage-flakes may be practically straight with the trace of the second cleavage in both flakes; the maximum symmetrical extinction-angle of the albite type of twin-lamellæ is, however, about 16°.

Labradorite. SiO_2 about 50%.—Extremely common as the typical felspar in basic diorites and andesites, dolerites, gabbros, and in the widely distributed basaltic lavas. Often alters to a grey saussuritic state. The coarse-grained hypersthene-gabbro of the east of Labrador (Paul's Id. and elsewhere) furnishes schillerised examples, with an exceptionally beautiful play of colours when polished. This iridescence can usually be seen on turning a rough specimen about in the hand in a good light.

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[1] "British Pillow Lavas," *Geol. Mag.* (1911), 202 and 241.

[2] W. T. Schaller, *U.S. Geol. Survey*, *Bull.* 509 (1912), 40.

Opt.—The high symmetrical extinction-angles of the albite-type of twin-lamellæ (about 30°) afford a useful character.

BYTOWNITE.—Named from Bytown, the old name of Ottawa.

Anorthite. SiO_2 43·08, Al_2O_3 36·82, CaO 20·10 %.—Though well-developed crystals of anorthite are rare, and are mostly illustrated in collections by small examples from the metamorphosed limestones of Monte Somma, felspars approaching pure anorthite are common in basic igneous rocks, as, for instance, in the olivine-gabbro of Carlingford Mountain, Co. Louth.

CELSIAN. $BaAl_2(SiO_4)_2$.—A rare barium anorthite. Triclinic. G. = 3·3. See Hyalophane.

CHAPTER XVI

THE SILICATES. ALLIES OF THE FELSPARS

The Felspathoids.

THE Felspathoids, or Felspathids, as they were originally named in France, form a group of silicates that supplement the felspars in certain igneous rocks, or even take their place, playing a similar part as light-coloured aluminous silicates in contrast with a darker ferromagnesian series. In composition they resemble felspars, in being aluminium silicates with potassium, sodium, or calcium; but the proportions in which the constituents occur make a profound difference in their crystallographic characters. The presence of chlorine in sodalite, one member of the group, suggests a link with the scapolite series; but the introduction of sulphur in the felspathoids nosean and haüyne is a very special feature. An unusual proportion of alkali in regard to the silica-percentage of the originating magma tends to the development of felspathoids, and the rocks containing them are somewhat unusual types of trachyte, andesite, and basalt, or of their more coarsely crystalline representatives.

Leucite. $(K,Na)Al(SiO_3)_2$. K_2O 21·5 when sodium is not present; SiO_2 55·0 %; Na_2O rarely more than 4 %.—Colourless to greenish and greyish-white; translucent varieties rare. Lustre vitreous to almost dull in the common opaque crystals. Cubic I at temperatures above 500°, and retaining at ordinary temperatures the characteristically cubic form of the icositetrahedron $\{211\}$, the angles of which have varied slightly during cooling from the original hot condition (Fig. 112). There seems no need, however, to describe this form as a tetragonal or rhombic combination, though optical tests show that repeated lamellar twining and lack of isotropism have set in.[1] Small crystals are sometimes almost granular, and at first sight resemble amygdaloidal infillings of cavities in the scoriaceous lavas in which they occur. H. = 5·5—6. G. = 2·5.

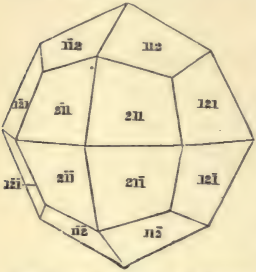

FIG. 112.—Crystal of leucite.

Leucite is a common mineral in certain areas and very rare elsewhere. In the trachytes, andesites, and basalts, and even the ultrabasic melilite-basalts, of Central Italy it is as prominent as the felspars. The lavas of Vesuvius, with about 47 % of silica, 21 of alumina, and 6 of potash, serve as a type of the basic rocks in which leucite may be expected to arise. Where the silica-percentage is higher, as in the trachytes, orthoclase may occur side by side with leucite. Leucite is unknown in rocks that have consolidated in the depths of the earth's crust; but large pseudomorphs having its crystalline form, and consisting of granular orthoclase and nepheline, occur in some of these crystalline masses, as in a grey-green porphyritic rock from near Rio de Janeiro in Brazil.[2] The rarity of leucite in rocks older than the Cainozoic era indicates that it is liable to break up into other forms, and it has also been suggested that leucite is unstable under considerable pressure. By introduction of water and substitution of sodium for potassium, leucite alters to analcite.

Tests.—The only mineral with which leucite is liable to be confused is analcite; but leucite is soluble in HCl without forming a jelly, and is infusible before the blowpipe. Gives an exceptional potassium flame when treated in a sodium carbonate bead as described on p. 160. See also p. 275.

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[1] For the grouping of the lamellæ and the conclusions that have been drawn from them, see Lévy and Lacroix, "Les Minéraux des Roches" (1888), 231.

[2] See O. A. Derby, "Nepheline Rocks in Brazil," *Quart. Journ. Geol. Soc. London*, **47** (1891), 260, where the work of Hussak and others on these pseudomorphs is described.

Opt.—Refr. index 1·51. Colourless; often shows numerous inclusions, regularly grouped within the crystal. These are often portions of the glass in which the leucite has developed. Outline octagonal or nearly circular. Thick sections show bright interference-colours; but these tone down into low grey tints as the section is thinned, and in ordinary rock-slices only light and dark lamellæ, due to the complex twin-structure, are revealed. Small crystals are usually isotropic, as if the warping influences set up during cooling had not affected them.

Nepheline. $(Na,K)_8Al_8Si_9O_{34}$ = the orthosilicate (Na,K) $AlSiO_4$, with a small excess of silica.—H. W. Foote and W. M. Bradley[2] give reasons for regarding this excess as variable, and as representing silica present "in some form in solid solution." Na_2O about 16 and K_2O 6 %. Colourless and transparent when fresh, but readily decomposing to analcite, natrolite, or granular micaceous pseudomorphs, when it becomes dull and easily overlooked in a rock-mass. Hexagonal IV, the third order hemimorphic character being revealed by corrosion-figures. Usually in small short hexagonal prisms terminated by basal planes, the vertical sections being nearly square. H. = 5·5. G. = 2·6.

Elæolite is massive nepheline, resembling quartz when it occurs in crystalline rocks, but with a somewhat resinous lustre, whence its name. Nepheline is found in igneous rocks that are rich in soda, as in the syenites of the Christiania district, the trachytes (phonolites) of North Bohemia, and in some unusual types of basalt. It occurs in the British Isles in an unaltered condition in the nepheline-nosean-trachyte of the Wolf Rock off the south coast of Cornwall.

Tests.—Soluble in HCl, giving gelatinous silicic acid, whence its name (*νεφέλη*, a cloud).

Opt.—The outlines, small hexagons and rectangles, are characteristic in rock-slices; often clouded and brown through decomposition. The irregularly bounded grains in nepheline-syenites may be distinguished from quartz by this decomposition, but should be chemically tested in the rock itself. Uniaxial; negative. Refr. indices, $\omega = 1·545$, $\epsilon =$ about 1·540.

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[1] *Amer. Journ. Sci.*, **31** (1911), 25, and **33** (1912), 439.

Birefringence weak, about 0·005, resembling that of the alkali-felspars which are often associated with it.

SODALITE. $Na_4(AlCl)Al_2(SiO_4)_3 = 3Na_2Al_2(SiO_4)_2 \cdot 2NaCl$. —Colourless to greenish-grey, but often a bright blue in granular and coarse examples. This blue colour is lost on heating. C. Giesecke and T. H. Holland have described greenish sodalites, from Greenland and India respectively, which flush rose-pink on being fractured, the greenish tint being recovered in a few hours. Transparent to opaque. Cubic I; the rhombic dodecahedron and cube are common forms. H. = 5·5—6. G. = 2·3.

Fairly frequent in igneous rocks rich in sodium, as a companion of soda-orthoclase and nepheline.

Tests.—Soluble in HCl, leaving a jelly of silicic acid. Strong sodium flame.

Opt.—Isotropic. Sections usually square or six-sided (sections of {110}). Refr. index 1·48, a little above that of fluorspar, from which transparent sodalite must be distinguished by chemical tests.

NOSEAN. $Na_4 (NaSO_4Al) Al_2 (SiO_4)_3 = 3Na_2Al_2 (SiO_4)_2 \cdot 2Na_2SO_4$ (compare with sodalite).—Colourless to dull brown when altered. Transparent when fresh. Cubic I, commonly as rhombic dodecahedra or octahedra. Occurs often with leucite or nepheline, in trachytic lavas, as in the phonolite of the Wolf Rock off the South Cornish coast.

Tests.—Soluble in HCl, leaving a jelly; sulphur reaction after fusion with sodium carbonate.

Opt.—Isotropic; but the larger crystals sometimes show grey interference-tints like those of leucite. Sections commonly six-sided or square; their outline is often corroded by intrusion of the groundmass of the lava, which produces a strong dark zone, spreading inwards from the surface of the crystal. Sections thus often exhibit black borders (Fig. 113). Minute inclusions numerous, often arranged in rectilinear series, which cross one another. Small crystals, since they so frequently yield hexagonal

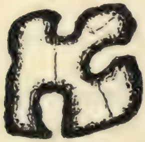

FIG. 113.—Thin section of nosean in trachyte, showing corrosion by the matrix.

sections of octahedra, etc., are difficult to distinguish from those of nepheline; but the abundance of such sections, which are all isotropic, will suggest nosean. The zeolitic pseudomorphs that are common are usually coloured a dusky brown in rock-slices.

HAÜYNE. $(Na_2, Ca)_2(NaSO_4Al)Al_2(SiO_4)_3 = 3(Na_2, Ca)Al_2(SiO_4)_2.2CaSO_4$.—Compare with nosean, of which haüyne is, in fact, a calciferous form. Colourless, but usually blue, and thus attracting the eye in many grey trachytic lavas. Cubic I, like nosean; occurs like nosean, and sometimes with it, in lavas rich in sodium.

Tests.—Microchemical tests have been used to distinguish haüyne from nosean; the minute crystals when attacked by HCl on the cleaned surface of a rock-slice, give, with a drop of H_2SO_4, a precipitate of radial bunches of gypsum. Yields sulphur like nosean in the silver coin test.

Opt.—Like nosean, but the blue tint often remains, even in thin sections. The colour is sometimes concentrated near the centre, and is sometimes, on the other hand, stronger in a marginal zone.

Lapis Lazuli is a rock associated with crystalline limestone, and mainly consisting of a blue cubic mineral, which is allied to haüyne, but which contains some sodium sulphide. (See Miers, "Mineralogy," p. 450.)

Scapolite Division.

The scapolites form a series of aluminium silicates with calcium or sodium or both, approximating to orthosilicates, with meionite at one end and marialite, which introduces a little chlorine, at the other. If, following Tschermak, the meionite molecule be styled Me, and that of marialite Ma, wernerite may be written $Me_3Ma_1–Me_1Ma_2$, and mizzonite $Me_1Ma_2–Me_1Ma_3$. The species are isomorphous, crystallising in Class I of the tetragonal system, mostly in prismatic forms closed by low bipyramids. Colourless to white or brownish. While scapolites crystallise at times in metamorphosed limestones, in the neighbourhood of igneous masses, their chief interest lies in their appearance as granular replacements of felspar. J. W. Judd[1] has traced the passage from a rock consisting of lime-soda felspar and pyroxene to a granular mass consisting of scapolite and amphibole.

The species are as follows :—

MEIONITE. $Ca_4Al_6Si_6O_{25}$. SiO_2 40·5 %.—H. = 5·5. G. = 2·7.

Wernerite (Scapolite).—See above. H. = 5·5. G. = 2·7.

MIZZONITE (Dipyre).—See above. H. = 5·5. G. = 2·62.

MARIALITE. $Na_4Al_3Si_9O_{24}Cl$. SiO_2 64 %.—H. = 5·5. G. = 2·6. The specimens commonly styled marialite usually have the composition Me_1Ma_4.

Tests.—The scapolites fuse fairly easily, but decompose only slowly in HCl.

Opt.—The uniaxial character is easily observed with convergent light. Negative. Refr. indices about 1·56 (scapolite has $\omega = 1{\cdot}566$, $\epsilon = 1{\cdot}545$). Hence there is practically no relief; but granular examples are distinguished from felspar or from quartz in the same rock-slice by their stronger birefringence. This is in mizzonite 0·015, in wernerite 0·021, and in meionite as high as 0·036.

Vesuvianite Division.

Vesuvianite (Idocrase). — Formula uncertain, owing to abundant inclusions, but is a basic calcium aluminium silicate, with some magnesium, fluorine, and water. Lévy and Lacroix state the composition as $H_2Ca_8Al_4Si_7O_{29}$. SiO_2 about 38 %. Translucent, greenish to brownish. Externally forms typical tetragonal crystals of Class I, with stout first and second order prisms closed by low bipyramids of both orders and basal planes (*wiluite* type). $a : c = 1 : 0{\cdot}3798$. Sometimes as elongated prisms, grouped radially, resembling members of the epidote division. Doubt has been thrown on the tetragonal nature of vesuvianite owing to the complexity of its structure as revealed between crossed nicols. H. = 6·5. G. = 3·4.

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[1] "On the processes by which a plagioclase felspar is converted into a scapolite," *Min. Mag.*, **8** (1889), 186. For references to the origin of the scapolite in this and other instances, see Clarke, "Data of Geochemistry," *U. S. Geol. Survey*, *Bull.* 491 (1911), 384.

Vesuvianite occurs, like the scapolites, in contact-altered limestones, as at Vesuvius in the ejected blocks of Monte Somma. Common where limestone has been invaded by a granite magma.

MELILITE. — Formula uncertain: F. W. Clarke gives $(Al,Fe)_2(Ca,Mg,Na_2)_6Si_5O_{19}$.[1] A calcium magnesium iron aluminium silicate; SiO_2 about 42 %. Yellowish. Tetragonal I; occurs as small prisms or interstitially. In the leucitic lava of Capo di Bove near Rome, melilite forms a ground in which the small leucite crystals are embedded. Melilite arises in basic and ultrabasic igneous rocks, where felspar is excluded.

Opt.—Pale yellow in sections. Refr. indices near 1·63; birefringence low (0·005). Sometimes shows curious peg-like inclusions, which are thin rods expanded at one end and regularly arranged.

The Zeolites.

The zeolites are grouped together from the fact that they give off water at somewhat low temperatures,[2] fusing readily, and usually with a boiling or swelling up. The name is derived from ζέω, "I boil." They are hydrous aluminium silicates with potassium, calcium, or sodium, or all of these. Barium, as in the felspar series, is occasionally present.

The zeolites are typically colourless or white, occasionally yellowish. The only departure from this pale aspect is when they become strikingly red, as in the case of some stilbite crystals. They occur well crystallised in the cavities of igneous rocks, and develop as products of alteration, and when waters leach out materials from the porous mass. They often form, in consequence, radial bunches, filling the steam-vesicles and contributing to the amygdaloidal character of the altered rock. Analcite also separates out as a primary constituent in the ground-mass of lavas and igneous sheets rich in sodium.

The lime-soda felspars and the felspathoids contribute to the formation of zeolites, while the alkali-felspars yield muscovite and kaolin. Zeolitic pseudomorphs after nepheline and nosean are common in phonolite, as at the Hohentwiel, near the Lake of Constance, while the cavities of andesites and basalts, as may be seen throughout the county of Antrim, are frequently occupied by various species. In rock-slices, radial masses of zeolites may be observed partially replacing prismatic groups of felspar, and larger and smaller crevices are infilled.

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[1] "Data of Geochemistry" (1911), 378.

[2] On the water in zeolites, see H. A. Miers, "Mineralogy" (1902), 489.

The hardness of radial and fibrous specimens is difficult to determine; but it will be found that the powder of most zeolites will scratch glass, and their H. = about 5·5; G. = very generally 2·2. Refractive indices lower than that of balsam; birefringence generally low.

Natrolite. $Na_2Al_2Si_3O_{10}.2H_2O$. — Rhombic; elongated prisms, and often in groups of fibrous needles. A very common species, arising from felspar, nosean, etc.

Tests.—Fusible at 2 of the scale, without intumescence. Strong sodium flame. Decomposed by HCl with formation of a jelly.

Opt.—Refr. indices, $\alpha = 1{\cdot}477$, $\gamma = 1{\cdot}489$. Slowest ray vibrates parallel to the length of the prismatic crystals (*c*-axis). The fibres show straight extinction parallel to their length.

Stilbite. $(Ca,Na_2)Al_2(Si_3O_8)_2 . 6H_2O$. — This may be compared with the polysilicate albite in the felspar series; Iddings, however, writes the formula as a metasilicate, $H_4(Na_2,Ca)Al_2(SiO_3)_6 \cdot 4H_2O$. Colourless, commonly white, and sometimes bright red. Pearly lustre conspicuous on cleavage-planes (010). Monoclinic I, but elongated along the *a*-axis, and assuming a rhombic form by interpenetrant twinning, the twin-plane being the basal plane. The four planes at each end of the crystal, resembling those of a rhombic bipyramid, are in reality those of the prism, one pair belonging to one of the interpenetrant forms and one to the other. Perfect clinopinacoidal cleavage. Occurs often in flattened sheaf-like groups, constricted in the middle. H. = 3·5—4.

Tests.—Intumesces during fusion. Decomposed by HCl without formation of a jelly.

Opt.—Refr. indices close to 1·50. The crystals or fibres elongated along the *a*-axis may show extinction at 0° to 8° from their long direction, according as they are viewed perpendicular to (001) or (010).

Analcite.[1] $NaAl(SiO_3)_2.H_2O$. Na_2O 14·1%.—A sodium leucite with one molecule of water. Colourless and transparent to opaque white. Lustre of opaque varieties vitreous (compare leucite). Cubic I, typical form the icositetrahedron, {211}, as in leucite (Fig. 112). Crystals often large, in cavities of altered basaltic and other igneous rocks. Also occurs as a groundwork in some lavas rich in sodium, as already noted, where it appears to be an original constituent.

Tests.—Distinguished from leucite by fusing easily and by a jelly being formed on decomposition by HCl. Strong sodium flame.

Opt.—Isotropic, but commonly shows anomalous grey interference-tints, which are conspicuous in thick rock-slices. Usually granular in outline, or fitting in between the other minerals. Refr. index 1·487.

CHABAZITE.—Formula uncertain, but a hydrous silicate of aluminium, calcium, and sodium, with some potassium. Miers and Iddings represents the molecule as fundamentally $CaAl_2(SiO_3)_4.6H_2O$. Colourless and transparent. Trigonal IV, common form a rhombohedron with angles over polar edges 94° 46′, so that the crystals resemble cubes. As they are often interpenetrant twins, they may be mistaken at first for fluorspar. H. = 4—4·5. G. = 2·1.

Tests.—Soluble in HCl without formation of a jelly.

Opt.—Refr. indices close on 1·48.

GMELINITE. $Na_2Al_2(SiO_3)_4.6H_2O$.—A sodium chabazite. Trigonal IV; the positive and negative unit rhombohedra are often combined, as in quartz, producing an apparently hexagonal form.

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[1] The original name "Analcime" seems to have had the "m" introduced into it erroneously. Analyses of analcite show a variable excess of silica and water over the amounts represented by the accepted formula here given. H. W. Foote and W. M. Bradley (*Amer. Journ. Sci.*, **33**, 1912, p. 433), from numerous new analyses, regard other silicates as entering into analcite isomorphously in solid solution, such as H_2SiO_5 and $Na_2Al_2Si_6O_{16}.3H_2O$.

APOPHYLLITE. $H_{14}K_2Ca_8(SiO_3)_{16}\cdot 9H_2O$. — The formula varies according to the way in which the water is distributed by various authors. Apophyllite is sometimes removed from the zeolites, since it parts with very little water at 100°. Some fluorine replaces part of the oxygen. Colourless and transparent. Tetragonal I, or possibly rhombic; often in short square prismatic forms resembling cubes. Perfect basal cleavage. H. = 4·5—5. G. = 2·35.

Tests.—Decomposed by HCl without formation of a jelly.

Opt.—Refr. indices close to 1·533. On the anomalies observed with convergent polarised light, see Miers "Mineralogy" (1902), 440, and Iddings, "Rock Minerals" (1911), 287. Whatever reading has to be given to the crystals as we now find them, it seems probable that they were tetragonal at the time of their formation.

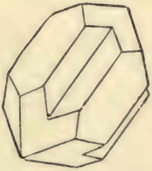
FIG. 114.—Crystal of harmotome.

HARMOTOME. $H_3(K_2,Ba)Al_2(SiO_3)_5\cdot 4H_2O$. BaO may equal 20%.—Colourless to white. Monoclinic, and often twinned like stilbite, so as to produce apparently rhombic forms. Two of these twins are often associated as a quadruplet, producing a right-angled cross when the form is viewed down its axis of elongation (*a*-axis) (Fig. 114). H. = 4·5. G. = 2·5.

Tests.—Decomposed by hydrochloric acid without formation of a jelly. Fusible at a higher temperature than most zeolites.

Opt.—Refr. indices, $\alpha = 1\cdot503$, $\gamma = 1\cdot508$.

CHAPTER XVII

THE SILICATES. MICAS, PYROXENES, AND AMPHIBOLES

The Micas.

RECEIVING their name from their bright reflective power as they lie associated with other minerals, the micas are among the best known silicates. They crystallise in the monoclinic system, though some are nearly rhombic and others nearly hexagonal; and the characteristic crystals are six-sided plates, in which the vertical axis is short, while the basal planes are broadly developed. The perfect basal cleavage adds to their lustre by admitting air along the parting-planes in exposed specimens. Numerous glancing platy inclusions may also develop along these planes, producing a shimmering effect. Cleavage-plates of extreme thinness can be flaked off, and are perfectly flexible. They have hence been used as translucent shades for candles and as chimneys for gas-burners, often under the trade name of "talc." These plates are, moreover, elastic. Large crystals of colourless mica have a commercial value, and smaller material is worked up into non-inflammable "mica-boards."

The micas have a hardness of 2·5 to 3, giving a characteristic grating sound as they are scratched by the knife-point; but they are not scratched by the thumb-nail, being thus distinguished from talc and the chlorites. G. = 2·8—3.

The micas are hydrous aluminium silicates with potassium (more rarely sodium or lithium), magnesium, or iron. Fluorine may appear, especially in some of the light-coloured species. They are sometimes divided into alkali-micas and ferro-magnesian micas; but it must be remembered that biotite, the type of the latter series, commonly contains 9% of potash, and often as much total alkali as muscovite, the typical "alkali-mica." The main difference lies in the silica and alumina, both of which are reduced in percentage as iron and magnesium are introduced. The magnesian or ferromagnesian series is, then, a real one, and the other series may be styled, in contrast, "micas poor in iron and magnesium." These two divisions correspond in practice to "dark micas" and "light-coloured micas" respectively.

Groth has conveniently treated the micas as orthosilicates. F. W. Clarke[1] holds that they are in the main orthosilicates, with some admixture of polysilicate molecules. The acid from which they are derived may be represented as $H_{12}(SiO_4)_3$; a rare species *kryptotile* actually possesses the formula $H_3Al_3(SiO_4)_3$. Monovalent, divalent, or trivalent elements may replace the twelve atoms of hydrogen in the acid in various groupings, such as $R'_3R'''_3$, or $R'_2R''_2R'''_2$, or $R'_3R''_3R'''_1$. This view has greatly simplified the representation of these complex silicates.

The presence of magnesium or iron, or both, almost invariably reduces the optic axial angle, so that many of the dark micas and the lighter coloured phlogopite appear almost uniaxial in thin cleavage-plates or sections. The optic axial plane is sometimes the clinopinacoid and sometimes perpendicular to it; but in the latter case, as is seen in muscovite, it is so highly inclined to the basal plane as to render the cleavage-plates perfectly serviceable for displaying an optic axial picture in convergent polarised light.

The micas are very common as original constituents of igneous rocks containing 75 to 60 % of silica, such as granites and diorites, but are less freely found in the basic series. They develop abundantly where argillaceous masses are affected by contact-metamorphism or by pressure acting over wide areas, such pressures being no doubt combined with a rise of temperature. Mica-schists, with their crumpled and gleaming surfaces of foliation, are thus the commonest metamorphic rocks.

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[1] "Data of Geochemistry" (1911), 373.

Micas arise also in slates as a first sign of foliation, aiding the remarkable parting-planes in the rock known as slaty cleavage, through their platy surfaces being arranged parallel with one another. G. P. Scrope pointed out as far back as 1822 that a rock with mica arranged in parallel layers would tend to slide and flow along these layers under earth-pressures, and this observation has been largely utilised by students of dynamic metamorphism.

Detrital micas, worn in minute fragments from older rocks, form part of the fine material of clays, and coarser flakes are found in most sandstones. Muscovite alters little in the course of rock-denudation and transport; but the ferromagnesian micas pass into the still softer chlorites.

MICAS POOR IN IRON AND MAGNESIUM.

These are decomposed by HCl only after prolonged digestion.

Muscovite. $H_2KAl_3(SiO_4)_3$.—Iddings gives the theoretical composition on this basis as SiO_2 45·2, Al_2O_3 38·5, K_2O 11·8, and H_2O 4·5. Colourless to various shades of brown or grey-brown. The six-sided plates are common in granites, and include zircon, rutile, etc., which appear as little spots breaking the glancing surfaces. Very large crystals, two feet or more in diameter, occur in some veins of the coarse granites that are misnamed "pegmatites." These rocks are mined for commercial material, notably in India and the eastern United States.

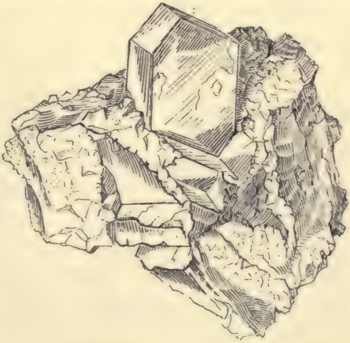


FIG. 115.—Muscovite in granite, Bamle, Norway.

Muscovite is a mineral of deep-seated origin, and does not separate out under the conditions of consolidation that prevail in lava-flows. Hence it occurs in granites and quartz-porphyries, but not in rhyolites. A considerable quantity of silica seems necessary for its production, since any micas arising in syenite, where plenty of potassium is available, are of the ferro-magnesian type. Muscovite is, however, the common mica in mica-schists.

Muscovite, moreover, develops abundantly as minute flakes as an alteration-product within potassium felspars, and is washed out into the residual "clays" when the felspar crumbles down. Several minerals become converted into soft micaceous pseudomorphs during hydration. The massive material of these pseudomorphs has been styled *Pinite*, and is found replacing nepheline, andalusite, etc.

Sericite, a term often used by petrographers, is also muscovite.

Opt.—Colourless to very faintly yellowish in thin sections. The inclusions of radioactive minerals cause brown pleochroic halos (p. 207), which are sections of the regions influenced round about the inclusion. Sections not parallel to (001) appear as elongated rectangles, with ragged edges in rock-slices, and a very distinct cleavage parallel to their longer sides. Extinction takes place practically parallel and perpendicular to this cleavage. Approximate refr. indices, $\alpha = 1{\cdot}560$, $\beta = 1{\cdot}595$, $\gamma = 1{\cdot}600$. The α-axis is nearly perpendicular to the basal cleavage. The birefringence is thus weak in basal sections, though the relief is fairly marked; in vertical sections, which, of course, show cleavage, the birefringence is strong (0·04), and interference-colours, usually high pinks and greens, appear only in truly thin slices. These tints serve readily to call attention to colourless mica in rock-sections that contain also well-cleaved prisms of clear felspar. Compare Fig. 116.

The difference of refractive index in vertical sections for rays vibrating respectively parallel and perpendicular to the cleavage-traces produces a twinkling effect like that seen in calcite (p. 227), when the section is rotated above the polariser, as in testing for axis-pleochroism; little relief is seen when the vibration-plane of the polariser is perpendicular to the cleavage-traces.

The optic axial plane is perpendicular to (010), and the typically wide axial angle is well seen on cleavage-flakes with convergent polarised light, where the apparent angle in air is 50 to 70°. In such flakes, the trace of the optic axial plane, determined by the position of the "eyes" in the convergence-figure, is the direction of vibration for the slow rays.

FUCHSITE is a muscovite with some of the aluminium replaced by chromium. It has a brilliant green colour, and occurs in some schistose rocks.

PARAGONITE is like muscovite, but with the potassium replaced by sodium. It is far rarer than mere chemical considerations would suggest.

LEPIDOLITE, in addition to the muscovite molecules, introduces molecules of $(Li,K)_3Al\,F_2\,Si_3O_8$ (Clarke). It resembles muscovite in appearance, but is often faintly pink. It is the source of much commercial lithium, and Li_2O may equal 5 to 10%. Gives a lithium flame. Optic axial angle large, the apparent angle in air being sometimes 84°. Optic axial plane parallel to (010).

MICAS RICH IN IRON AND MAGNESIUM.

These are more easily attacked by HCl than the preceding series.

ZINNWALDITE links lepidolite with the ferriferous micas, since it contains 10% of Li_2O, 10% of FeO, and also some ferric oxide. It looks like muscovite, and occurs in the altered granitic rocks of the tin-mining areas in the Erzgebirge. Optic axial angle large.

PHLOGOPITE. $H_2KAlMg_3(SiO_4)_3$.—Silica about 40 and magnesia about 27%. Pale bronze-coloured. Much of the commercial mica of Ontario is phlogopite.

Opt.—Refr. indices near those of muscovite, but the small difference between β and γ allows only low colours in cleavage-plates and basal sections; as in muscovite, both the β and the γ axes lie practically in the basal plane. Optic axial angle small, the apparent angle in air being perceptible in the

Ontarian specimens in thick flakes only. Hence usually appears uniaxial. Optic axial plane parallel to (010).

Biotite. $(H,K)_2(Mg,Fe'')_2(Al,Fe''')_2(SiO_4)_3$. SiO_2 about 35, Al_2O_3 about 15, and Fe_2O_3, FeO, and MgO together about 30 %. K_2O commonly 9 %.—Pale bronze to, far more commonly, deep bronze-black or black. Sometimes deep green. Biotite is the common species in intermediate and basic igneous rocks. A bronzy and almost metallic appearance arises on oxidation, and flakes found in soils and gravels are often mistaken by untrained observers for alluvial gold.

Opt.—Forms of sections and cleavage like muscovite. Hexagonal outlines of the basal sections often seen in the well-developed crystals in lavas. Coloured zoning is common. Shows various tints of brown or green in thin sections. The face-pleochroism is strong, the colours being darkest in basal sections, which are often deep red-brown, while the vertical sections in the same rock-slice are straw-yellow (Fig. 116). Axis-pleochroism not seen in basal sections, since these are practically isotropic, but extremely striking in all sections that show the cleavage-traces. Darkest tint when the vibration-plane of the polariser is parallel to the cleavage-traces. Refr. indices, $\alpha =$ about 1·55, $\gamma =$ about 1·58. Birefringence therefore fairly strong; in some exceptional examples it rises to 0·08. The colour of the mineral often masks the interference-colours, but high tints are seen in some thin sections that show the cleavage-traces. As in muscovite, the α-axis nearly coincides with the c-axis of form.

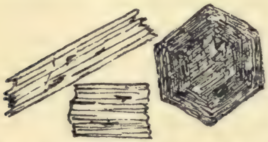


FIG. 116.—Vertical and basal sections of biotite in andesitic lava.

Extinctions in sections showing cleavage are practically parallel and perpendicular to the cleavage-traces. H. S. Jevons (*Geol. Mag.*, 1893, 82) has pointed out that such sections may be distinguished from vertical sections of brown amphibole by the occurrence in them of light patches even in positions of general extinction. These are due to the irregularities produced in the soft flexible mineral during grinding.

The absorption for rays vibrating parallel to the cleavage-traces is sometimes so great that, when a single nicol is employed below the section of biotite, the mineral section acts as an analyser, transmitting scarcely any rays when the vibration-plane of the polariser is parallel to the cleavage-traces. Under such conditions, any small doubly refracting mineral lying in the thickness of a rock-slice between the polariser and the mica will be viewed, as it were, between crossed nichols, and will show interference-colours when its vibration-traces, as must usually happen, are not parallel to those of the mica. This explains the spots of colour frequently seen when biotite is being examined with the polariser only for axis-pleochroism.

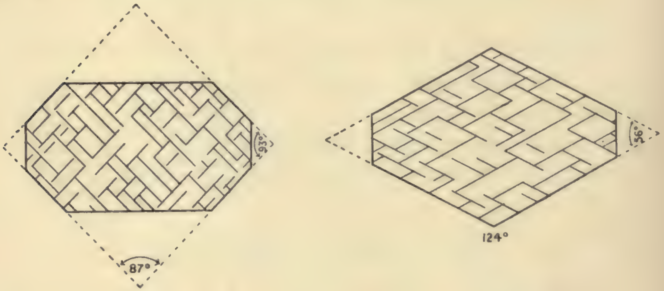
Optic axial plane usually parallel to (010); but the small angle of the optic axes renders basal sections practically uniaxial. The angle in air varies from 0° up to the entirely exceptional 56° recorded for a specimen from the Alban Hills. Lévy and Lacroix state the actual angle as 0° to 30°.

The Pyroxenes and Amphiboles.

These two series are closely allied, and greater stress was laid in former days on their differences than would now be the case. Petrography remains in consequence burdened with a double nomenclature for basic igneous rocks, depending on the presence of pyroxene or amphibole, although it now appears that the same molecules can build up species in either series, and that structural rearrangements can convert a member of one series, when once established, into the member that corresponds with it in the other.

Haüy, in 1801, invented both names. Pyroxene means "stranger to fire," and was given under the mistaken and Wernerian view that pyroxenic rocks were deposited as sediments from water. Amphibole merely means "a doubt." Both the series of minerals now included under these terms have rhombic, monoclinic, and triclinic representatives, the monoclinic being by far the most abundant. The forms that we have to classify under these distinct systems resemble one another in being typically prismatic, vertical pinacoids being also developed. A common type thus includes {110}, {100}, and {010}. The terminating planes are bipyramids, domes of both kinds, or basal planes. Two cleavages are present, parallel to the planes of the unit prism.

The essential difference between pyroxenes and amphiboles lies in the unit prism angles, which are near 90° in the pyroxenes, and near 124° and 56° in the amphiboles. Broken fragments and irregularly bounded sections, owing to the prevalent cleavages, allow this fundamental character to be recognised (Fig. 117).



(i) (ii)

FIG. 117.—Horizontal sections of (i) augite and (ii) hornblende, as seen in rock-slices.

The two series consist primarily of the metasilicate $R'' SiO_3$, where R'' is Mg, Ca, or Fe''. Monovalent elements and the trivalent Fe''' and Al may, however, be introduced, as in ægirine, $NaFe'''(SiO_3)_2$, or in spodumene, $LiAl(SiO_3)_2$, or in the molecule $Na(Al,Fe''')(SiO_3)_2$, which is associated with $R''SiO_3$ in soda-augite. The two commonest types, moreover, include molecules of the composition $R''R'''_2SiO_6$.

The silica-percentage consequently varies considerably, from 64 in spodumene down to about 45 in common augite and hornblende. The hardness is usually about 5·5 to 6, spodumene being exceptional with nearly 7. G. = very generally a little over 3. Most forms are fusible at about 3·5 of von Kobell's scale.

Both pyroxenes and amphiboles arise in igneous rocks where iron and magnesium and calcium are prevalent. Calcium species are produced in limestone by contact-metamorphism, together with calcium-garnets and other silicates. Amphiboles often result from paramorphic changes in pyroxene, and are the more stable forms. Very many rocks of early geological date that are now rich in hornblende—the bulk of the diorites, for example—were probably pyroxenic at the time of their consolidation. Though primary amphibole appears in some basic lavas, laboratory-experiments on the fusion of amphibole result in the crystallising of pyroxene from the molten mass. A highly interesting study of the inter-relation of the forms that can be built up with the same molecular constitution has been made by E. T. Allen, F. E. Wright, and J. K. Clement.[1]

The common aluminous species of pyroxene and amphibole decompose in nature to chlorite; pyroxene often passes previously through an amphibolic stage. The non-aluminous magnesian species alter into serpentine. When such changes have set in, the hardness is much reduced.

The following table will illustrate the relations of the principal species:—

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[1] "Minerals of the composition $MgSiO_3$," *Amer. Jour. Sci.*, **22** (1906), 385.

	PYROXENES.	*Composition.*	AMPHIBOLES.
RHOMBIC.	Enstatite	$MgSiO_3$	A corresponding artificial amphibole.
	Bronzite	$(Mg,Fe'')SiO_3$	Anthophyllite.
	Hypersthene	$(Mg,Fe'')SiO_3$	—
	—	$\left\{\begin{array}{c} m(Mg,Fe'')SiO_3 \\ n(Mg,Fe'')Al_2SiO_6 \end{array}\right\}$	Gedrite.
MONOCLINIC.	Clino-enstatite	$MgSiO_3$	A corresponding artificial amphibole.
	Wollastonite	$CaSiO_3$	—
	Diopside	$CaMg(SiO_3)_2$	—
	—	$CaMg_3(SiO_3)_4$	Tremolite.
	—	$Ca(Mg, Fe'')_3(SiO_3)_4$	Actinolite.
	Acmite and Ægirine	$NaFe'''(SiO_3)_2$	—
	Spodumene	$LiAl(SiO_3)_2$	—
	Augite	$\left\{\begin{array}{c} m(Ca, Mg, Fe)SiO_3 \\ n(Mg,Fe'')(Al,Fe''')_2SiO_6 \end{array}\right\}$	Hornblende.
	Soda-augite	$\left\{\begin{array}{c} (Mg,Fe'')SiO_3 \\ Na(Al,Fe''')(SiO_3)_2 \end{array}\right\}$	Aluminous soda-amphiboles.
TRICLINIC.	Rhodonite	$MnSiO_3$	—
	Babingtonite	$\left\{\begin{array}{c} (Ca,Fe'',Mn)SiO_3 \\ Fe'''_2(SiO_3)_3 \end{array}\right\}$	—
	—	$Na_4Fe''_9AlFe'''(Si,Ti)_{12}O_{38}$	Ænigmatite.

RHOMBIC PYROXENES.

The rhombic forms were first observed as common rock-forming minerals by Whitman Cross, who pointed out the "straight extinctions" of many pyroxenes in rock-slices in regard to the bounding edges of their sections. It will be remembered that in minerals of the rhombic system the α, β, and γ axes, which control the directions of extinction, are respectively parallel to the three crystallographic axes. W. Cross also noticed the remarkable pleochroism of the more strongly coloured rhombic pyroxenes, as compared with the feeble pleochroism of monoclinic forms.

Bronzite and hypersthene were originally marked off by the schillerisation and consequent lustre of certain well-known altered examples, and much that was once called hypersthene proves to be a schillerised augite, known as diallage. Tschermak proposed a chemical classification, styling the varieties practically free from FeO enstatite, those with FeO 5 to 15% bronzite, and those with more than 15% hypersthene. To these J. W. Judd adds *amblystegite*, a revival of an old name given by vom Rath, for varieties with FeO 25 to 35 %.

The α-axis corresponds with the a-axis, the β-axis with the b-axis, and the γ-axis with the c-axis, the vertical axis of form.

The pleochroism increases in intensity with the iron content, and hypersthene appears greenish or pink-brown, according to the position in which the prisms or grains lie in a rock-slice. The axis-pleochroism gives the following tints: α-axis red-brown, β-axis yellow-brown, γ-axis bluish-green. Enstatite shows hardly any pleochroism.

The crystal-forms, except for the planes that cap the prisms, closely resemble those of the more common monoclinic pyroxenes; but the a-axis unites, as in all rhombic crystals, the obtuse angles of the prism, which here measure 92°, while in monoclinic pyroxenes the clinoaxis has to be taken as the a-axis, and unites the acute angles. Hence, in comparing the common eight-sided basal section of a rhombic pyroxene with that of a monclinic one, the a-axis in one must be set so as to be parallel with the b-axis in the other. This difficulty is not due to differences in the structure of these closely allied minerals, but merely to the methods that we find most convenient in arranging crystals of different systems for description.

ENSTATITE contains less than 5% of FeO, and SiO_2 nearly 60%. Faintly greenish or brownish; colourless to faint yellow-brown in thin sections. Sometimes granular. Unusually large grey-green pseudomorphs in serpentine occur in the apatite-bearing dykes at Bamle, in southern Norway.

Opt.—Refr. indices, $\alpha = 1{\cdot}656$, $\beta = 1{\cdot}659$, $\gamma = 1{\cdot}665$; birefringence consequently weak compared with that of monoclinic pyroxenes. The low interference-colours often call attention to enstatite in a rock-slice, and the frequency of extinctions parallel to the boundaries of the prismatic sections then adds confirmation.

BRONZITE.—Pleochroic in thin sections.

HYPERSTHENE. SiO_2 a little over 50%.—Best known in large dark-brown schillerised crystals from the coarse hypersthene-labradorite-diorite of St. Paul's Island, off the coast of Labrador. G. = 3·5.

Opt.—Plechroism marked, in tints of pink-brown and blue-green. Sometimes granular, as in the "pyroxene-granulites" (recrystallised dolerites) of southern Saxony, in which the mineral must be distinguished from the pink isotropic garnets found in the same rock-slices.

MONOCLINIC PYROXENES.

The prevalent crystals in these species consist of the almost rectangular prism, the two principal vertical pinacoid pairs, and a "positive" hemibipyramid, $\{\bar{1}11\}$. The planes of $\{\bar{1}11\}$ unite in an inclined edge at either end of the *c*-axis, and might be read as clinodome planes. A plane, however, occasionally occurs in the zone (100) (001), making an angle of 74° 10′ with the vertical axis and sloping in the opposite direction to that of the frequently occurring common terminal edge. This plane is selected as the base, and its trace on (010) is shown in diagrams illustrating the optical properties of monoclinic pyroxenes. The obtuse angle referred to in descriptions of these diagrams is thus not that commonly seen in vertical sections of these pyroxenes. Twinning with (100) as twin-plane and composition-plane is frequent, resulting in crystals with a re-entrant groove at one end. Sometimes this twinning is repeated in a lamellar fashion in a limited region on either side of the central composition-plane.

The optic axial plane is parallel to the clinopinacoid; the true optic axial angle is close on 60° (in air over 100°), the value being higher in the species rich in sodium. The oblique extinctions are very serviceable. The *c*-axis is used as the reference-line, and the greatest angle of extinction will, of course, be read off in sections parallel to (010), the exceptional sections parallel to (100) giving straight extinction. The common form of sections parallel to (010) is rhomboidal (Fig. 119); the cleavage-traces appear in them as one series, as in all sections parallel to the *c*-axis, and indicate the direction of this axis. If this direction is set upright in the field of the microscope, it is convenient to measure the extinction-angle by rotation towards the side on which the upper acute angle of the section lies, formed by the traces of {100}, or the prism, and {111}. The extinction-angle reaches 52° in some augites, and drops to 5° or even less in species rich in sodium. These latter require to be carefully distinguished from rhombic forms, and, by their cross-sections and cleavages, from amphiboles, which have usually a small extinction-angle in the prismatic zone.

Since the bisectrix concerned in the measurement of these extinction-angles is the γ-axis in diopside and augite, while it is the α-axis in the sodium-species and in ægirine and acmite, the ordinary quartz-wedge shows compensation when directed nearly along the *c*-axis in the sodium-species, and a heightening of colour when directed along the line joining the acute angles of common vertical sections of diopside and augite.[1]

The refractive indices of monoclinic pyroxenes range from 1·67 to 1·80; usually about 1·70, so that good relief is exhibited. The birefringence is fairly strong, about 0·02. In contrast with the rhombic species, the monoclinic species show distinctly richer interference-tints than the felspars in the same rock-slices.

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[1] As already noted, the obtuse and acute angles here referred to are the reverse of those shown in optical diagrams and seen in sections bounded by the traces of {100} and {001}.

CLINO-ENSTATITE.—The mineral to which this name has been given by W. Wahl is the monoclinic form of $MgSiO_3$, known in certain meteorites and possibly as an intergrowth with enstatite in terrestrial igneous rocks.[1]

WOLLASTONITE. $CaSiO_3$.—Colourless. The forms differ from the general type of monoclinic pyroxene in being often tabular and elongated along the *b*-axis, while the cleavages are parallel to the orthopinacoid and the base. The prism-angle (110) ($1\bar{1}0$), is, however, typically pyroxenic, being 87° 18′. H. = 4·5—5. G. = 2·85.

Occurs mostly in contact-altered limestones.

Tests.—Decomposed by HCl with formation of a jelly. The solution gives a strong calcium flame.

Opt.—Refr. indices about 1·63. Birefringence about 0·014.

Diopside. $CaMg(SiO_3)_2$.—Nearly colourless to pale green. The occasional introduction of chromium gives rise to bright green varieties. Monoclinic II, but almost always showing the symmetry of Class I. The basal plane is more frequently developed than in augite, making an angle of 74° 10′ with the *c*-axis. Prism-angle measured over the edge (110) ($1\bar{1}0$) is 87° 12′. Cleavage prismatic, but also basal. H.=5·5. G.=3·2. Occurs commonly in contact-altered limestones, and in the "amphibolites" produced from them in extreme cases, where it is associated with hornblende and pink-brown calcium garnet. Also in some igneous rocks. Alters to tremolite, serpentine, or even talc.

Tests.—Not decomposed by HCl.

Opt.—Refr. indices, α = about 1·673, γ = 1·700. Extinction-angle on (010) 38° to 44°.

ACMITE and ÆGIRINE, $NaFe'''(SiO_3)_2$.—Acmite is brown, ægirine deep green. Acmite is terminated by steep pyramid-planes. These minerals are the pyroxenic constituents of igneous rocks very rich in sodium, such as the nepheline-syenites of the Christiania district.

Opt.—The green colour of ægirine especially attracts attention in sections; face-pleochroism yellow-green to deep green;

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[1] Allen, Wright, and Clement, *Amer. Journ. Sci.*, **22** (1906), 431; and H. Michel, *Centralblatt für Min.* (1913), 161.

brown tints in the rarer acmite. Axis-colours in ægirine, α-axis green, β-axis olive-green, γ-axis yellow-green. The γ-axis is almost perpendicular to the length of the clinopinacoidal section, since the α-axis deviates only 5° from the c-axis. The darkest tint thus occurs, as in hornblende, practically parallel to the length of prismatic sections. Extinctions also practically parallel to the long axis of prismatic sections; the pleochroic tints, however, do not resemble those of rhombic pyroxene.

SPODUMENE. $LiAl(SiO_3)_2$.—A greenish or greyish-white pyroxene found in some granites, usually in rather elongated and well-cleaved prismatic forms. Prism-angle 87°. H. = 6·5—7, but sometimes lowered through alteration. G. = 3·18. *Kunzite* is a pink-violet variety (see p. 148).

Tests.—Lithium flame.

Augite. $m(Ca,Mg,Fe'')SiO_3 \cdot n(Mg,Fe'')(Al,Fe''')_2SiO_6$. — SiO_2 about 50, CaO 20, and MgO 14 %. Deep green to black, and commonly opaque. $a:b:c = 1{\cdot}09:1:0{\cdot}59$. Provides typical pyroxenic forms (Fig. 118), often flattened from front to back by the prominent development of {100}. The cross-sections are thus usually octagons, often elongated along the b-axis (Fig. 117, i.). Basal plane somewhat rare. Augite is by far the commonest pyroxene, playing a large part in basic igneous rocks, but passing in geological time into the amphiboles actinolite or hornblende. *Uralite* is a pseudomorph in green hornblende, retaining the outer form of augite, but showing the cleavages and pleochroism of amphibole. Hence the paramorphic change is often styled *uralitisation*. DIALLAGE is an augite schillerised on (100), so that parting-planes, practically forming a new and predominant cleavage, occur parallel to the orthopinacoid. Diallage arises within augite, usually as a preliminary to uralitisation. Augite often alters into chlorite.

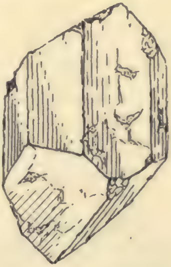
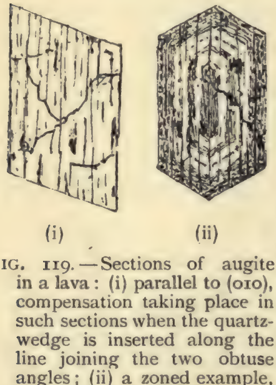


FIG. 118.—Augite, Schima, Bohemia.

The hardness of unaltered augite is 5·5. G. = 3·2.

Tests.—Only slightly attacked by HCl. Fuses at about 3 to a dark glass.

Opt.—Colour of sections yellowish to straw-brown; purple in some cases. Lighter in cross-sections of the prism. The colour is occasionally differently distributed in sectors of the crystal-section, producing what is known as the *hour-glass structure*. Slight differences in the positions of extinction for these sectors show that the areas are of different chemical composition. Zoning, marked by abundant inclusions or by colour-variations, is very common (Fig. 119, ii.). Pleochroism feeble, but thick sections sometimes show purple-brown and straw-yellow tints. Refr. indices, $\alpha =$ about 1·70, $\beta =$ about 1·71, $\gamma =$ about 1·73. Birefringence consequently strong in sections parallel to (010). Relief marked. Extinction-angle on (010) 38° to 52° from the vertical axis; commonly about 45°, which easily distinguishes augite from rhombic pyroxenes and from amphiboles. In irregularly bounded sections, such as the grains in dolerites and gabbros, the prevalence of yellow-brown rather than green tints, the very feeble pleochroism, and especially the almost rectangular cleavage-mesh in basal sections, are useful characters.


(i) (ii)

IG. 119.—Sections of augite in a lava: (i) parallel to (010), compensation taking place in such sections when the quartz-wedge is inserted along the line joining the two obtuse angles; (ii) a zoned example, cut parallel to (100).

Soda-augite. $(Mg,Fe'')SiO_3 . Na(Al,Fe''')(SiO_3)_2$.—The formula here given represents the association of a normal pyroxene molecule with that of an aluminous ægirine. It is probable, however, that many stages occur connecting ordinary augite and ægirine. The soda-augites are dark green or black, but are distinguished from ordinary augite by their pleochroism in sections, the cross-sections being yellowish and the vertical sections green. Colour-zoning common. The axis-pleochroism is also marked, though not so strong as in the green amphiboles. The extinction-angle, measured from the *c*-axis, as described on p. 305, towards the ordinary upper acute angle of the section (010), is near 55°, and sufficiently distinct from that of ægirine, which is over 90° when the γ-axis is utilised. A further increase of some 35° would be required to bring the other bisectrix, the α-axis, into coincidence with the vertical guide-line, a condition realised, or passed by 5°, in ægirine.

Soda-augites are extremely common in rhyolites, trachytes, phonolites, and in some andesites; also in the more coarsely crystalline representatives of these rocks.

TRICLINIC PYROXENES.

RHODONITE. $MnSiO_3$.—Rose-pink (see p. 186). Triclinic, but the vertical zone resembles that of the monoclinic pyroxenes, in that the prism-angle is 87° 32′. H. = 6. G. = 3·6. Occurs on a large scale in the Ural Mountains, slabs being polished for ornamental purposes.

Tests.—Easily fusible. Often effervesces in HCl, owing to admixture of calcite or dialogite. Manganese reactions in the beads.

BABINGTONITE. $(Ca,Fe'',Mn)SiO_3.Fe_2'''(SiO_3)_3$; or perhaps $mCa_2(Fe'',Mn)(SiO_3)_3 . nFe_2'''(SiO_3)_3$. — Miers regards the essential babingtonite molecule as $FeSiO_3$. The eight-sided outline of cross-sections of the prism has a pyroxenic aspect. Occurs rarely as black crystals in granitic rocks.

RHOMBIC AMPHIBOLES.

These are much rarer than the rhombic pyroxenes. The silica-percentage is about 55. Extinction parallel to the long axes of the prisms. ANTHOPHYLLITE occurs in some metamorphic rocks, and in needle-like forms in the zones of interaction that are found in many basic igneous rocks between altering olivine and felspar.

MONOCLINIC AMPHIBOLES.

On the whole, these species contain more magnesia in proportion to lime than the corresponding pyroxenes. The prevalent crystals consist of the prism, with angles of about

124° and 56°, the clinopinacoid pair, a clinodome {011}, and a "positive" hemiorthodome {$\bar{1}$01}. The prismatic crystal is thus six-sided, and capped at each end by three rhomboidal planes, which remind one of a rhombohedron until the interfacial angles are examined. {011} was at one time regarded as the unit pyramid, corresponding with that in augite, until crystals of amphibole grown round diopside were discovered at Russell in New York State. The vertical axes of the two minerals are here the same, and the two principal vertical pinacoids are respectively parallel in the pyroxene and the amphibole, while the basal pinacoid of the pyroxene is nearly parallel with the edge formed by the clinodome-planes in the enveloping amphibole. Twinning occurs in amphibole on (100), but less frequently than in the corresponding pyroxenes; twinning simple.

The optic axial plane is almost always parallel to (010), as in the monoclinic pyroxenes; the true optic axial angle is often as large as 80°. The γ-axis is directed in (010) as in the monoclinic pyroxenes, but usually at a less angle to the vertical axis of form (about 12° only). The consequent small angle of extinction in prismatic sections distinguishes monoclinic amphiboles from monoclinic pyroxenes other than ægirine and acmite. Refractive indices 1·60 to 1·75. Relief and birefringence much as in the monoclinic pyroxenes; but the birefringence rises to 0·07 in hornblendes rich in iron.

TREMOLITE. $CaMg_3(SiO_3)_4$, exemplifying the general richness in magnesia rather than in lime that prevails among monoclinic amphiboles. SiO_2 nearly 58%.—Colourless to faintly greenish or brownish. Often elongated and even fibrous. H. = 5·5. G. = 2·9. Occurs in some altered limestones.

Tests.—Not attacked by HCl.

Opt.—Extinction-angle on (010) about 16°. Refr. indices, $\alpha = 1{\cdot}606, \gamma = 1{\cdot}634$. Recognisable from other colourless minerals in rock-slices by its cleavages at 124° and the lozenge-shaped form of its cross-sections. See, however, the Epidote series.

ACTINOLITE.—A ferriferous tremolite. Green, often in well-developed translucent needle-like forms. Occurs very commonly in small and almost fibrous crystals as an alteration-product of pyroxene, and occasionally of olivine, shooting out as green needles in various directions across the area once occupied by these minerals. Develops, in rather shorter forms, as a product of the passage of a dolerite into an amphibole-schist.

Opt.—Extinction-angle and refractive indices as in tremolite. Pleochroic, the vertical sections showing darker tints of green. The axis-pleochroism shows the darkest tints parallel to the γ-axis, that is, nearly along the length of prismatic sections.

Asbestos is an extremely fibrous form of tremolite or actinolite, usually crystallised across the crevices of rocks. The prisms are so thin as to be flexible and wool-like in the mass, and are worked up into various forms as a non-inflammable material.

Hornblende. Composition like augite, but on the whole more magnesian. SiO_2 about 45, MgO about 13, and CaO about 12 %. Hence the apparently paramorphic change that so often takes place from augite into hornblende may involve a loss of calcium.—Deep brown or green to black, and commonly opaque. $a : b : c = 0{\cdot}55 : 1 : 0{\cdot}29$, the angle (110) $(1\bar{1}0)$ being close on 124°. In rock-forming examples, the vertical axis of the prism is fairly long, and the clinopinacoid-planes are subordinate to the prism-planes. H. = 5·5. G. = 3·2. Hornblende is a very common amphibole, but is not so frequent as pyroxene as a primary constituent of lavas. It occurs, however, as skeletal and tufted forms in the glassy rhyolites (pitchstones) of Arran in the Clyde, and as richly brown crystals (*basaltic hornblende*) in many andesites. Hornblende is very common in the deep-seated rocks syenite and diorite, and in aphanite, which corresponds with the pyroxenic rock dolerite, and which often passes under earth-pressures into hornblende-schist. Hornblende develops, sometimes on a bold blade-like scale, at contacts of granite with basic masses, and the hornblende-granites often result from the absorption of dolerites by a granitic magma and from subsequent recrystallisation. Where the contact-surface can be traced, such granites are found to be richer in hornblende near their margins. This absorbed material, separating as hornblende, passes further at times into brown mica.

Hornblende usually alters into chlorite, which is the ultimate and stable product of so many aluminous ferromagnesian silicates.

Tests.—Slightly attacked by HCl. Fuses at 3·5 to 4 to a dark glass.

Opt.—Colour of sections brown, straw-yellow, or green. Zoning not so common as in augite; but hornblende crystals are often attacked and "resorbed" by the matrix of the lava from which they have developed. A black zone of residual material then borders their sections, and sometimes only an opaque granular residue remains.

Pleochroism strong, the lightest tints appearing in cross-sections of the prism. Green prismatic sections and pale straw-yellow sections, showing the six-sided outline and the cleavage-lattice (Fig. 117, ii), thus often appear in the same rock-slice. Axis-pleochroism very marked, even in pale-coloured specimens; darkest tints nearly parallel to the length of the prism, as in ægirine.

Refr. indices, $\alpha =$ about 1·63, β about 1·64, γ about 1·65. It will be remembered that the γ-axis is nearly parallel with the *c*-axis of form. Extinction-angle on (010) about 12°, which provides a useful character.

ALUMINOUS SODA-AMPHIBOLES.—Several species may be grouped here, remarkable even among amphiboles for their striking pleochroism. Na_2O about 7 or 8 %. GLAUCOPHANE and RIEBECKITE are both slate-blue; the former has the composition $(Fe'',Mg)SiO_3.NaAl(SiO_3)_2$, and the latter $Fe''SiO_3.2NaFe'''(SiO_3)_2$. Riebeckite thus appears to consist of two ægirine molecules to one molecule of the fundamental babingtonite type. The pleochroism of both these minerals gives in sections deep blue to straw-yellow tints, and the axis-colours are equally remarkable.

Glaucophane forms, with epidote, considerable masses of amphibole-schist in the Alps of Piedmont, the blue colour being easily seen in the cliff-sections. A similar schist occurs in Anglesey. Riebeckite appears as a slate-blue constituent of the fine-grained granites of Mynydd-mawr, near Snowdon, and of Ailsa Craig, in the Clyde.[1]

KROKYDOLITE or CROCIDOLITE is another blue species, occurring like asbestos in veins in Griqualand West, and best known by its pseudomorphous form "tiger's eye." The latter consists of orange-brown limonite and chalcedony, retaining the fibrous character and silky lustre of the massive krokydolite. Krokydolite is like riebeckite, but richer in $FeSiO_3$. ARFVEDSONITE is a black species found in nepheline-syenites, with some 8 % of Na_2O and as much as 35 % of FeO. Its sections are coloured a rich brown.

TRICLINIC AMPHIBOLES.

ÆNIGMATITE (COSSYRITE), from Pantelleria and Greenland, is allied to the amphiboles, but has prism-angles of 114° and 66°. G. = near 3·8. Ænigmatite has been regarded as a titanosilicate, and specimens from Greenland contain over 7 % of TiO_2, and only 38 % of SiO_2; in the mineral from Pantelleria the joint percentage of these is represented as SiO_2 43·5 %, and titanium has not been recognised.

Talc Division.

TALC. $H_2Mg_3(SiO_3)_4$. SiO_2 63·5, MgO 31·7 %.—In composition talc is a tremolite with hydrogen in place of calcium. White or pale green or brown, colourless in thin flakes. Rhombic (?), occurring in platy forms, aggregated together, with perfect cleavage, which is regarded as basal. H. = 1. G. = 2·75. Plates flexible but not elastic.

Occurs as an alteration-product of enstatite and other non-aluminous magnesian silicates. Sometimes forms great foliated masses among metamorphic rocks (talc-schists), as at Crohy Head in the west of Donegal. Massive types are known as *soapstone*, and are sought after for "French chalk" and as a lubricating material. The greasy feel, due to the softness and flakiness of the material, resembles that of graphite.

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[1] On the origin of glaucophane-schists, see S. Franchi, *Boll. Reale Comitato d'Italia* (1902), 255. On Riebeckite, see Warren and Palache, *Proc. Amer. Acad. Arts and Sci.*, **47** (1911), 145 and 156.

Tests.—Not decomposed by HCl. Infusible; splinters give in O.F. with cobalt nitrate a good pale pink magnesium reaction.

Opt.—Birefringence somewhat higher (0·05) than that of the micas.

CHLORITOID, $H_2(Fe,Mg)Al_2SiO_7$, may be mentioned here, since it appears to have a molecular constitution like that of the aluminous molecule in the pyroxenes and amphiboles, with the addition of one molecule of H_2O. An ally of chloritoid, with much more silica and some 6 % of MnO, is called OTTRELITE; for this, Iddings suggests the composition $H_2(Fe,Mn)Al_2Si_2O_9$, which brings to mind the chemical structure of kaolin and serpentine. The crystalline system of these two minerals is uncertain (monoclinic or triclinic), and they both form platy deep grey crystals, rather lustrous, with a hardness of 6·5. G. = about 3·5. They occur in schists, their hardness being the first character that calls attention to their crystals.

Opt.—Chloritoid is strongly pleochroic in sections; axis-colours blue to yellowish-green. These colours might suggest iolite, but the refractive indices are high in chloritoid (about 1·75), and the relief is consequently strong.

CHAPTER XVIII

THE SILICATES. SOME ROCK-FORMING ORTHOSILICATES

Olivine Division.

Olivine. $(Mg,Fe)_2SiO_4$. SiO_2 about 40, MgO about 50, FeO about 10%.—Yellowish-green, transparent when fresh, and looking like grains of brightly reflecting gum in the dark matrix of many basaltic lavas. Rhombic I. $a : b : c = 0·465 : 1 : 0·586$.

Crystalline form not commonly seen, but shows the prism, both vertical pinacoid pairs, and both domes, with bipyramid planes and basal planes sometimes in addition. Cross-sections in almost any direction give elongated octagonal or hexagonal forms; the faces are usually rounded towards a granular form. Sections appear characteristically as in Fig. 120. H. = 6·5—7 when fresh. G. = 3·3. Olivine is found to occur more and more frequently as we pass from igneous rocks with some 60% of silica to the ultrabasic series, where almost pure olivine-rocks may actually arise. The rhombic pyroxenes seem to represent olivine where there is sufficient silica; but some ultrabasic crystalline masses consist of a rhombic pyroxene side by side with olivine. By developing at any early stage of consolidation, olivine becomes included in the other minerals, and often forms the spots that break the continuity of the reflecting cleavage-surfaces of large crystals of pyroxene, amphibole, or magnesian mica. On decomposition, it passes into serpentine, the consequent expansion being sufficient to cause radiating rifts in minerals round it, these cracks becoming filled with serpentine. Magnetite at the same time separates out, and darkens the mineral, so that its presence is easily overlooked in the rock-mass. It remains, however, readily recognisable in rock-slices, though in a few cases its place has been taken by fibres of actinolite, spreading from an enveloping amphibole or pyroxene.

Iddingsite is a platy translucent red decomposition product, which sometimes becomes substituted for the original olivine granule.

Olivine, or perhaps monticellite, may arise by contact-alteration in limestones, as at Monte Somma, in bands parallel with the surface of the invading mass. Such limestones were probably dolomitic at the outset.

Clear crystals are used as gems, under the name of *Chrysolite*.

Tests.—Soluble in HCl with formation of a jelly.

Opt.—Refr. indices, $\alpha = 1{\cdot}661$, $\beta = 1{\cdot}678$, $\gamma = 1{\cdot}697$. Birefringence and relief therefore strong. The high interference-colours call attention to residual granules of unaltered olivine in many masses of serpentine. One of the most characteristic features seen in sections is the yellow-green or blue-green serpentine, spreading from the surface and along the cracks (Fig. 120, ii). Cleavage is not seen in sections; but the serpentine builds up a meshwork of fibres lying in all directions, two sets of which must always lie in positions of maximum illumination between crossed nicols. Hence the appearance of a rectangular mesh in the serpentinous areas.[1] In modern lavas, such as those of the Pacific Islands, unaltered olivine shows as colourless sections of an elongated hexagonal form.

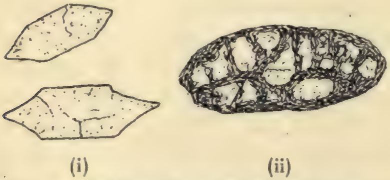
(i) (ii)

FIG. 120.—Thin sections of olivine in basalt: (i) unaltered, with characteristic outlines; (ii) granule altering into serpentine.

FORSTERITE, Mg_2SiO_4, MONTICELLITE, $CaMgSiO_4$, and

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[1] See G. Cole, "Aids in Practical Geology," ed. 6 (1909), 149 and 180.

FAYALITE, Fe_2SiO_4, are isomorphous with olivine. In fayalite, SiO_2 is as low as 30, and FeO as high as 70%, and the specific gravity rises to over 4; it forms with garnet the heavy rock known as eulysite, and is found in minute crystals in cavities of certain glassy rhyolites. Forsterite and monticellite both occur in contact-altered limestones or dolomite rocks.

The Garnets.

This common group of silicates has a type of formula that was formerly written symmetrically as $3RO.R_2O_3.3SiO_2$. This gives us the orthosilicate $R_3''R_2'''(SiO_4)_3$. R'' is usually represented by Ca, Mg, Mn, or Fe; R''' by Al, Fe, or Cr. The garnets are cubic (Fig. 121), especially affecting the rhombic dodecahedron, which is often combined with the icositetrahedron {211}, and the six-faced octahedron {321}. Cleavages parallel to the six pairs of planes of {110}, but not often seen in thin sections. H. = 7. G. varying from 3·1 to 4·3.

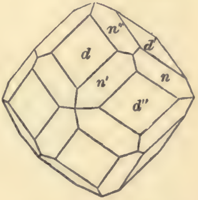

FIG. 121.—Crystal of garnet, with {110} and {211}.

Garnets almost invariably occur as products of metamorphism, usually where an aluminous rock has been raised to a high temperature. They are found in almost every mica-schist, and calcium varieties are common in altered limestones, gaining silica from the invading igneous rock and sometimes building up a granular mass. Garnets are abundant also in amphibolites, and in the corresponding pyroxenites known as "eclogites;" here again they probably have a metamorphic origin.

Pyrope occurs in serpentine, as at Zöptau in Moravia, having probably been an original constituent of the olivine-rock. The garnet in the serpentine necks of South Africa, as at Kimberley, appears to be derived from an underlying eclogite.

The garnets in veins of granite are usually derived from adjacent schists.

Garnets occasionally alter into softer products, known collectively as *kelyphite*. Chlorite is one of the most frequent materials, forming a dark green zone enveloping unaltered garnet.

Tests.—Most garnets fuse easily, an unusual feature in a gem-like mineral.

Opt.—Small specimens are isotropic; but larger crystals sometimes show, like leucite, anomalous interference-colours, in tints of grey. Refr. index close on 1·80, and relief consequently very marked.

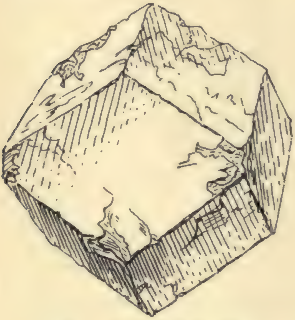

FIG. 122.—Almandine.

Almandine, $Fe_3Al_2(SiO_4)_3$, with SiO_2 36 %, is the common red garnet of mica-schists (Fig. 122). It remains pale pink even in thin sections. G. = about 3·3. Fusible at 3.

Pyrope, $Mg_3Al_2(SiO_4)_3$, is usually a clear translucent red, and forms most of the garnet used in jewellery.

Grossularite, $Ca_3Al_2(SiO_4)_3$, occurs as greenish or light brown crystals, often of large size, in contact-altered limestones. CaO about 37 %.

ANDRADITE (including MELANITE), $(Ca,Fe'')Fe_2'''(SiO_4)_3$, is green, brown, or black (melanite). G. = about 4. Beautiful small crystals of melanite, with colour-zoning in tints of brown, occur, from no very obvious cause, as primary constituents of some trachytic rocks, in localities far apart. This is the more remarkable since garnets scarcely ever occur in other lavas.

SPESSARTINE, $(Mn,Fe'')_3(Al,Fe''')_2(SiO_4)_3$, occasionally forms conspicuous and pale red crystals in granite.

UVAROVITE, $Ca_3(Cr,Al)_2(SiO_4)_3$ is coloured a rich bright green, like dioptase. It is nearly infusible. Rare, but occurs in ultrabasic rocks containing chromite.

Epidote Division.

Epidote and its allies are composed of $HR_2''R_3'''Si_3O_{13}$, which has been represented as an orthosilicate molecule in the form $R_2''(R'''OH)R_2'''(SiO_4)_3$. The division includes rhombic and monoclinic forms, and the long axis of the former has naturally been selected as the *c*-axis. The monoclinic forms, however, are elongated along the *b*-axis, so that what nature seems to have intended as a prism must be set horizontally, the crystallographic prism being represented by unimportant planes at the ends, as is the case in some tabular crystals of barytes.

Rhombic Forms.

Zoisite. $HCa_2Al_3Si_3O_{13} = Ca_2(AlOH)Al_2(SiO_4)_3$.—Light grey or brownish. Rhombic I. The prism-angle $(110)(1\bar{1}0)$ is 116° 26′, which corresponds well with that between (100) and (001) in epidote (115° 23′), the prismatic form in the latter, as above noted, being laid horizontally.

Perfect cleavage parallel to brachypinacoid. H. = 6·5. G. = 3·3.

Occurs in fibrous masses, resembling some vesuvianite, and commonly in amphibole-schists. In minute crystals is a common product of the alteration of calcium-felspars, when they pass into the dull grey state known as *saussurite*.

Tests.—Fuses with some intumescence before the blowpipe. Partly soluble in HCl.

Opt.—Sections colourless. Refr. indices all close on 1·7, and birefringence is thus weak (about 0·007). The low interference-tints distinguish zoisite from epidote, though the rhomboidal cross-sections and cleavage-traces are similar in the two minerals. Optic axial plane sometimes parallel to (010), and sometimes, but less commonly, to the basal pinacoid (001).

Thulite is a manganiferous zoisite, pink, with remarkable pleochroism, showing pink and yellow axis-colours in sections.

Monoclinic Forms.

Clinozoisite has the composition and pale colour of zoisite, but is monoclinic. Its birefringence is as a rule higher than that of zoisite.

Epidote. A zoisite with some 10% of Fe_2O_3, the ferric iron replacing aluminium. $HCa(Al,Fe''')_3Si_3O_{13} = Ca_2(AlOH)$

$(Al,Fe''')_2(SiO_4)_3$. SiO_2 about 38%.—Strong and deep yellowish green in fair-sized crystals, and a characteristic paler yellowish green when granular and diffused. Translucent. Monoclinic I, elongated along the *b*-axis, often in blade-like forms, with a sharp edge at each end formed by the meeting of the prism-planes. The zone of long planes includes as its most prominent features {100} and {001}, the angle between these, which is often seen in cross-sections, being 115° 23′. Compare with this the prism-angle in zoisite. Basal cleavage perfect, orthopinacoidal cleavage not so well developed; the occurrence of both, however, causes cross-sections of the elongated form to resemble those of an amphibole. H. = 6—7. G. = 3·4.

Epidote occurs quite commonly in small grains, making up considerable patches in rocks, as an alteration-product of calcium felspars and ferruginous silicates in association. Though more common in basic rocks, it occurs vividly at times beside the red alkali-felspar and colourless quartz in granites. Alteration into epidote toughens the rock-constituents, and the change may be contrasted with the production of chlorite and limonite, which induce decay.

Tests.—Partly decomposed by HCl. Fusible to a dark green glass like that given by actinolite.

Opt.—Colourless to yellow-green in thin sections. Pleochroism yellowish to green, but faint in thin sections. Refr. indices, $\alpha = 1{\cdot}730$, $\beta = 1{\cdot}754$, $\gamma = 1{\cdot}768$; birefringence therefore very much stronger than in zoisite, and stronger than that of other silicates liable to be mistaken for it, except unusually ferriferous amphiboles. The high interference-colours, associated with the strong relief, call attention to it in thin slices. Optic axial plane parallel to (010), with the α-axis nearly coincident in direction with the *c*-axis and the γ-axis therefore nearly perpendicular to (100); β-axis parallel to the *b*-axis, the length of the prismatic forms.

PIEDMONTITE is a manganese-epidote, in which Mn replaces Al and at times Fe. The analysis of the type from St. Marcel, near Aosta, shows Mn_2O_3 15%. The pleochroism becomes intense, α-axis yellow, β-axis pale pink, γ-axis strong pink. The handsome colour of the altered andesite of Djebel Dokhan in Egypt, known from its use by the Romans as the "antique red porphyry," is due to finely diffused manganese-epidote.

ALLANITE (ORTHITE). An epidote with cerium, didymium, and lanthanum in part replacing Al and Fe'''.—Yellowish to brown or, more commonly, black. Yellow-brown in thin sections, and strongly pleochroic, the darkest brown tints being parallel to the γ-axis. J. J. H. Teall has shown that allanite is more common in crystalline igneous and metamorphic rocks than might be supposed. It is often surrounded by an isomorphous zone of green epidote.

Prehnite Division.

PREHNITE. $H_2Ca_2Al_2(SiO_4)_3$.—Greenish, and resembling coloured smithsonite, but easily recognised by its lower specific gravity. Rhombic II, but usually massive, in mammillated groupings. H. = 6—6·5. G. = 2·9. Occurs in cavities of igneous rocks, and in crevices, like the zeolites, with which it has been sometimes classed.

Tests.—Fuses easily. Decomposed by HCl.

Staurolite Division.

STAUROLITE. $HFeAl_5Si_2O_{13}$. SiO_2 only 28, Al_2O_3 53 %.—S. L. Penfield[1] represents staurolite as an orthosilicate $Fe(AlO)_4(AlOH)(SiO_4)_2$. The impurities, as in vesuvianite, render analysis difficult. Brown; glassy lustre commonly interrupted by impurities; surface in the well known Brittany examples almost sandy. Rhombic I; often as interpenetrant cross-twins of somewhat stout prismatic forms twinned on a brachydome or a pyramid plane. The former type yields a rectangular cross (Fig. 123). Occurs in metamorphic schists; fine untwinned prisms are found with the St. Gotthard kyanite.

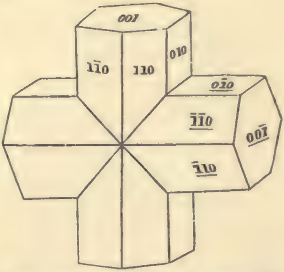

FIG. 123.—Crystal of staurolite twinned on a brachydome-plane.

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[1] "Contributions to Mineralogy" (1901), 213.

Opt.—Refr. indices near 1·74; $\gamma - \alpha = 0{\cdot}01$. Pleochroic; parallel to α and β axes yellow or green; γ-axis red.

IOLITE, Haüy, 1809. (DICHROITE, Cordier, 1809; CORDIERITE, Lucas, 1813).—The last of these names is in very general use. $H_2(Mg,Fe)_4Al_8Si_{10}O_{37}$ (Farrington, 1892). Blue, transparent, looking in rocks like lumps of rather faintly-coloured blue glass. H. = 7. G. = 2·65. Rhombic I, often granular. Occurs occasionally in granite, but far more commonly in schists and gneisses, especially as a contact-product. Alters easily to hydrous products, becoming soft and dull. By introduction of potash, muscovite and biotite may result, and "pinite" thus replaces iolite.

Opt.—Refr. indices near that of the balsam in thin slices, that is, close to 1·54; birefringence about that of quartz. Almost colourless when in thin sections, with pleochroic tints of faint blue (or violet-blue) and pale yellow. Thick pieces of the mineral show striking pleochroism, and give lighter tints of pale blue or yellow in sections parallel to the optic axial plane (100) and much deeper blue tints in those perpendicular to (100). Axis-colours darkest parallel to the β-axis, which is parallel to the a-axis of crystal-form.

In thin sections yellowish alteration-products are often seen spreading along the irregular cracks. Fibres of sillimanite are sometimes included abundantly in iolite in schists. Pleochroic halos (p. 207) occur round any radioactive inclusions.

CHAPTER XIX

THE SILICATES. SERPENTINE, THE CHLORITES, TITANOSILICATES, BOROSILICATES

Serpentine Division.

Serpentine. $H_4(Mg,Fe)_3Si_2O_9$. SiO_2 about 44 %.—Yellow, like threads of pale gold, in fibrous crystals, with silky lustre (*chrysotile* type), to pale green, deep green, and almost black in massive specimens. Ferriferous serpentine may alter to a red colour, and serpentine-rock may display a streaky structure in a great variety of green and red-brown tints. Probably rhombic, but well-formed crystals are unknown. H. = 2·5; sometimes appears harder through residues of olivine or inclusions. G. = about 2·5.

Chrysotile develops, like asbestos, across cracks, occurring in massive serpentine, and sometimes on such a scale as to be used in the asbestos trade. Massive serpentine, or granular serpentine among other minerals in igneous rocks, is almost invariably found on microscopic examination to be derived from the hydration of olivine, an excess of iron from the original olivine being sometimes thrown out as magnetite and darkening the serpentine. This relationship with olivine has been discussed on p. 315. Most olivine-rocks of remote geological age are now represented by serpentine-rocks.

Tests.—Decomposed by HCl. The softness as compared with the original olivine is characteristic.

Opt.—Blue-green or yellow-green in sections, often with traces of the irregular crack-structure of the original olivine and with the form of olivine grains (Fig. 120, ii.). Commonly in minutely fibrous aggregates. A rectangular mesh appears between crossed nicols, for the reasons assigned on p. 316.

Refr. indices little above that of the Canada balsam, 1·56 to 1·57; birefringence low, the interference-colours contrasting with the higher tints given by any residual cores of olivine that are left in the serpentinous aggregate.

GARNIERITE.—A hydrous magnesium nickel silicate, which has proved an important ore of nickel in New Caledonia. Bright yellowish-green; massive. Derived from serpentine-rocks, in which no doubt the nickel occurs as one of the deep-seated materials of the crust, having been brought to the surface by the ultrabasic igneous magma.

Tests.—Gives good nickel reactions with the fluxes, including the characteristic yellow bead in O.F. in microcosmic salt, which is so often obscured in other nickel ores by the presence of cobalt.

The Chlorites.

These minerals are named from their green colours, and are hydrous aluminium magnesium iron silicates. They resemble the ferromagnesian micas in being monoclinic, with a general six-sided platy form and a marked basal cleavage. The plates are sometimes associated along a curved and even vermiform axis, and chlorite in minute twisted groupings may be sometimes seen under the microscope in sections of veins of quartz. The cleavage-flakes are not elastic, though flexible, and the hardness is 1 to 2·5, so that all the species can be scratched with the thumb-nail. G. about 2·8.

The same optical variations occur here as in the micas, some chlorites being practically uniaxial and some clearly biaxial, with an apparent axial angle in air of over 80°. Refr. indices about 1·58, and birefringence sometimes very low, only rarely reaching 0·01, and becoming 0·001 in the species pennine. Optic axial plane parallel to (010).

Chlorites arise as decomposition-products from aluminous pyroxenes and amphiboles, and from ferromagnesian micas, and are not known as primary constituents of rocks. The silica set free at the same time often crystallises as quartz. Chloritisation causes many basic igneous rocks to become soft and valueless as road-metal. From these rocks the chloritic flakes become washed out into sediments; but they may arise in sedimentary masses, such as sandstone and shale, by the alteration of detrital silicates after the consolidation of the rock.

The grey-green colour in rocks, sometimes extending monotonously, as in North Wales, over hundreds of square miles, is almost invariably due to chlorite, wisps and flakes of which may be detected with the microscope between the unaltered grains of quartz or other colourless constituents. The chlorites thus share with iron hydroxides the control of the colour of broad landscapes.

Occasionally chlorite-schists occur, often containing well-crystallised magnetite (Fig. 81), and probably representing the final stage of foliated amphibolites.

The green linings to the cavities of altered scoriaceous lavas usually consist of chlorite.

Pennine. $H_8(Mg,Fe)_5Al_2Si_3O_{18}$. SiO_2 about 32, H_2O about 13 %.—A common species forming platy and fanlike groups.

Opt.—Refr. indices near 1·57, and birefringence very low (0·001). Isotropic for yellow light; hence, between crossed nicols, yellow rays can play no part in the production of interference-colours. The mineral is, however, biaxial and double refracting for light of other colours, though only low interference-tints can arise. An indigo-blue is characteristic. Pleochroic; parallel to α-axis green, γ-axis yellowish.

Clinochlore.—Composition like pennine, but with an optic axial angle up to 50° (apparent angle in air nearly 90°). $\gamma - \alpha = 0{\cdot}01$; interference-colours thus like those of serpentine. Pleochroism much like that of pennine.

Ripidolite is a species rich in iron, with silica as low as 25 %.

Green Earth Division.

Glauconite. A hydrous silicate of ferric iron and potassium, with some aluminium, magnesium, and calcium.[1]—Only known as fibrous and flaky aggregates, often with the form of the hollows of foraminiferal shells or sponge-spicules, in which the mineral has accumulated. H. about 2. G. about 2·3.

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[1] For analyses see "Deep Sea Deposits," *Challenger Reports* (1891), 378; and Collet and Lee, *Comptes rendus*, **142** (1906), 999, who point out that the iron is ferric in modern glauconite.

Glauconite occurs as small dark-green grains in many sands and sandstones, styled "greensands," and in clays, such as the Gault of England; also in limestone, as in the Kentish Rag and the so-called "chloritic chalk." In Antrim, greensands occur at the base of the local Cretaceous series which consist in greater part of glauconite. When struck with the hammer in the field, glauconitic rocks show a distinct green streak. The mineral can easily be crushed between two plates of glass, when its colour becomes similarly apparent.

The researches carried on by the *Challenger* expedition called attention to the common formation of glauconite in about 100 fathoms of water in modern seas. It is suggested that an interaction takes place between the decaying animal matter of small organisms and the marine salts, the green silicate ultimately occupying even the minute passages and tubules in shells and spicules. Perfect casts of a number of chambered foraminifera have been dredged up from Sydney harbour, with the shell adhering to them. In the course of time, the shells and even the spicules of siliceous sponges disappear by solution, and only the stable glauconite remains. Microscopic preparations have shown numerous four-rayed green casts of tetractinellid sponge-spicules throughout the flinty sandstones (cherts) of the English Lower Cretaceous beds, and glauconite grains from other formations usually possess the rounded outlines of the chambers of foraminiferal shells. Rocks rendered green by glauconite are known from all geological systems.

Opt.—Bright green in thin sections. Axis-pleochroism yellow to green where distinct crystalline flakes can be observed.

GREENALITE.[1] $(Fe,Mg)SiO_3 . nH_2O$, the magnesium being distinctly subordinate to the iron.—A green silicate found as grains, often oolitic, among the bedded iron ores of the Mesabi district, near Lake Superior, and no doubt the same as that which appears in thin sections of the oolitic iron ores of Silurian age in North Wales. Its composition shows it to be distinct from glauconite, and its mode of occurrence points to its being a siliceous replacement of material that was originally deposited as an ore of iron, possibly a carbonate.

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[1] C. R. van Hise and C. K. Leith, "Geology of the Lake Superior District," *U.S. Geol. Surv., Mon.* LII, 165 and 152.

GREEN EARTH, CELADONITE, ETC.—Under these names, various green silicates of magnesium and iron have been described, which occur as infillings of cavities in scoriaceous lavas. The presence of potassium in certain cases shows a possible relationship with glauconite. See also under Chlorites.

Titanosilicates.

Sphene (Titanite). $CaTiSiO_5$. TiO_2 40·8%. Yellow brown to reddish-brown, rarely green. Adamantine lustre. Monoclinic I, with the hemibipyramid (111) usually prominently developed, the angle over the edge (111) $(1\bar{1}1)$ being 136° 11′. The mineral takes its name from its double wedge-like forms. Cross-sections, such as are seen in rock-slices, are almost always shaped like a double wedge, this lozenge-form being distinctly narrower and longer as regards its two diameters than that given by cross-sections of amphibole or epidote. H. = 5. G. = 3·5.

Sphene is common in igneous rocks with about 65% of silica, such as syenites and trachytes, and in contact-altered basic rocks near junctions with granite. Unusually large brown crystals occur in Renfrew Co., Ontario. The whitish material arising during the alteration of ilmenite and titaniferous magnetite, which has been styled *leucoxene*, is believed to be sphene.

Tests.—Titanium reaction when dissolved in HCl after reduction with sodium carbonate.

Opt.—The elongated lozenge-form of sections is very characteristic. The cleavage being prismatic, its traces are not parallel to the boundaries of the ordinary rhomboidal sections. Usually yellow-brown, sometimes pink-brown. Only faintly pleochroic. Refr. indices approximately $\alpha = 1·89$,

$\beta = 1{\cdot}90$, $\gamma = 2{\cdot}00$. Hence the relief is stronger even than in garnet, and the birefringence, which may amount to 0·14 for $\gamma - \alpha$, is unusually strong in most sections. The consequent interference-colours, approaching high white, are rarely seen in sections. Sections, however, containing the α and β axes show a birefringence as low as that of rhombic pyroxene. Optic axial plane parallel to (010), which is parallel to the shorter diameter of the ordinary rhomboidal cross-sections.

Borosilicates.

Tourmaline. $H_9Al_3(BOH)_2Si_4O_{19}$, the hydrogen being replaced in part by Al, Na, Li, Mg, or Fe.[1]—Vitreous lustre, transparent to opaque. The common rock-forming variety, known to miners as *schorl*, is black; but colourless, pink, brown, green, and blue varieties are known, and zoned forms exist, in which pink and green layers are in striking juxtaposition. The large crystals from Madagascar afford handsome zoned examples. Trigonal II, crystals being hemimorphic on the *c*-axis (Fig. 42), often with a basal plane predominant at one end and groups of pyramid-planes at the other. Rock-forming examples are usually elongated along the *c*-axis and sometimes needle-like. $a : c = 1 : 0{\cdot}447$, hence the unit pyramid is not steep. The vertical planes are often a trigonal prism combined with the second order hexagonal prism $\{11\bar{2}0\}$. The trigonal form commonly predominates, and cross-sections are triangular, with modifications at the angles; very often the sides of the triangular form are curved, and striations due to repetition of faces run parallel to the *c*-axis on the faces of the vertical zone (Fig. 124). Conchoidal fracture. H. about 7. G. = 3 to 3·3. Pyroelectric (see p. 151).

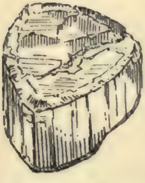

FIG. 124.—Zoned tourmaline.

Tourmaline is a common product of the action of subterranean gases in veins of granite, occurring at times with fluorspar and topaz, but far more frequently than either of these minerals. Black needles of "schorl" are often enclosed in secondary quartz in altered granites, and "schorl-rock," consisting of these two minerals, is a result of the prolonged attack of vapours on subterranean masses of granite. Tourmaline occurs also in contact-altered schists, along the margin of intruded granite.

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[1] S. L. Penfield and H. W. Foote, *Amer. Journ. Sci.*, **7** (1899), 97. The authors regard the group $Al_3(BOH)_2Si_4O_{19}$ as controlling the common characters of the many varieties of tourmaline and as allowing considerable divergence in the materials that replace the hydrogen.

Tests.—Its hardness, the form of cross-sections, and the absence of cleavage, distinguish it from amphibole. Variously fusible, but mostly with ease. Some specimens, when fused with fluorspar and potassium bisulphate, show the green flame due to boron.

Opt.—Cross-sections triangular, with curved sides, like mediæval shields, characteristic. No cleavage-traces. Colour usually yellow-brown or bluish, both tints often occurring in the same crystal. Strong pleochroism, basal sections showing the deepest tints; axis-colours darkest when the rays vibrate perpendicularly to the long axis of the prisms (see p. 114). Uniaxial and negative, so that the *c*-axis is the vibration-direction for the fastest rays. In amphiboles, this is approximately the vibration-direction for the slowest rays, and the darkest tint of the axis-pleochroism occurs parallel with it. Refr. indices, ω about 1·64, ϵ about 1·62; birefringence 0·02.

The strong absorption for the ordinary rays allows sections of tourmaline to act as polarisers or analysers, and interference-colours are thus sometimes seen, as is the case with biotite, in crystals lying between a section of tourmaline and the polarising nicol in the thickness of a rock-slice. The nature of these colours is revealed by their remaining the same when the analysing nicol is brought also into play (see p. 299).

AXINITE. $H_4(Ca, Fe'', Mn)_5(Al,Fe''')_4B_2(SiO_4)_8$. Ford[1] gives the general formula as $R_7''R_4'''B_2(SiO_4)_8$, on which the above is based.—Pink-violet to greyish; transparent. Lustre almost adamantine. Triclinic, in flattened acute-edged crystals. H. = 7. G. = 3·3. Occurs somewhat rarely, and generally as a product of contact-metamorphism.

[1] *Amer. Journ. Sci.*, **15** (1903), 195.

CHAPTER XX

CONCLUSION

ENOUGH has been said in the foregoing pages, though doubtless in a scattered way, to show that mineralogy is not merely a descriptive science, or primarily devised as a help to the prospector. Within the smallest crystal there are groupings of particles which, if we could get down among them, would appeal to our imaginations like an ordered system of planets and dominating stars. These groupings are already revealed to us as properties of certain kinds of matter, which in themselves are mutable and evolved. The conditions under which crystalline species endure may be external to them, or may result from some internal balancing of parts which gives them fixity through immense periods of time. Yet there may well be a succession among minerals, and their natural history is bound up with the evolution of the globe.

Their chemical and physical characters, which look so formal when set down on paper, have a new meaning for us when we seek out minerals across the earth. The solubility of calcite leads us into an underworld of limestone caves, and the decay of felspar has moulded for us the domes of granite moors. On seaward-stretching reefs we meet the wind that carries salt across the continents, and the desert sands still gleam for us with gypsum from forgotten lakes. We may view with equal admiration the liquid mineral that flows from the ice-fronts of Alaska, and that which lurks as glistening globes imprisoned in the Idrian mines. Everywhere for the mineralogist and the geologist "the earth is turned up as it were by fire; the stones thereof are the place of sapphires, and it hath dust of gold."

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